Climate Change Vulnerability Assessment of the Galápagos Islands

CONSERVATION INTERNATIONAL

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Ministerio del Ambiente

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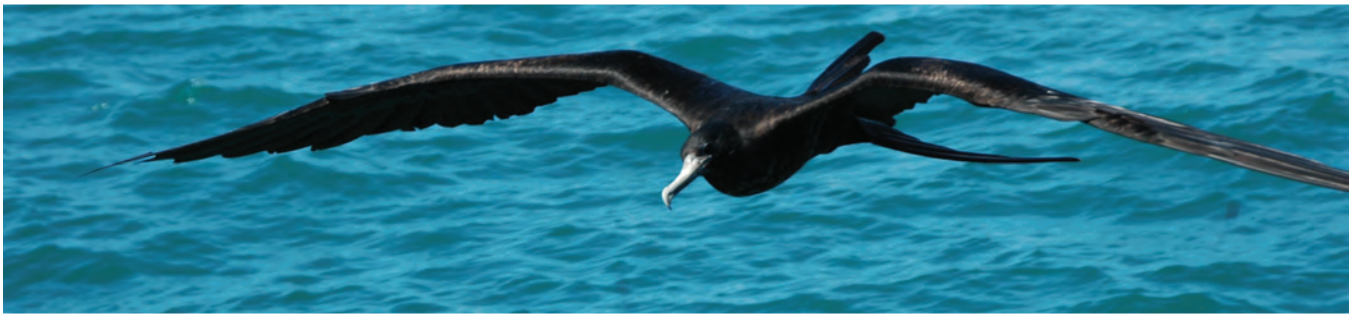

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PREFACE

The Galápagos Islands are among the many places in the world already experiencing the impacts of climate change. It is predicted that climate change will cause rising sea level, higher ocean temperatures and more acidic waters. As the ocean largely regulates the climate, changes in ocean temperatures and currents are already altering the frequency, intensity, and distribution of storms, floods, heat waves, and the amount and distribution of rainfall. The unique and endemic biodiversity of the Galápagos is at risk. In addition, the loss of Galápagos biodiversity directly impacts its local human communities as their livelihoods are dependent primarily on nature-based tourism, fisheries, and agriculture, all of which are dependent on these threatened natural resources.

In September 2008, Conservation International and World Wildlife Fund (WWF), in cooperation with the Ministry of Environment of Ecuador and the Galápagos National Park, conducted a vulnerability assessment to gauge the likely impacts of climate change on marine and terrestrial ecosystems of the Galápagos and the human communities that are dependent upon them. The assessment evaluated the vulnerability of the Galápagos Islands to climate change and determined the priority actions needed to ensure that the Galápagos can adapt to future climate conditions.

This study –including an international workshop– was conducted as part of a year-long commemoration of the 50th anniversary of the Galápagos National Park and brought together experts on the Galápagos marine and terrestrial environments, climate scientists, social scientists, government officials and local stakeholders, all working under a common agenda: the need to maintain and increase the resilience of Galápagos biodiversity. This agenda turned into a real commitment under the *Declaration of Santa Cruz*, signed by the Ecuadorian Ministry of the Environment, the Galápagos National Park Service, Conservation International, WWF, the experts that contributed to this study and all the workshop participants.

This report contains the scientific studies that underpin the immediate and substantial actions needed to increase the adaptive capacity of Galápagos' ecosystems and the people that depend on them. Adapting to climate change is the only solution to ensure ecosystems and human societies can survive and maintain their well-being when exposed to climate change impacts. These studies will support the development of the Climate Change Adaptation Plan for the Galápagos Islands, an initiative of the Ministry of Environment's Climate Change Undersecretary, integrated into the National Climate Change Strategy of Ecuador.

Conservation International and WWF are committed to continuing our support to the Ministry of Environment and the Galápagos National Park in their efforts towards ensuring that the biodiversity of the Galápagos is protected and can adapt to future conditions for the benefit of the Galápagos society and its future generations.

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ACKNOWLEDGEMENTS

This document is the result of a collective effort and would not have been possible without the contributions of many people and organizations.

Conservation International and WWF would like to acknowledge the organizations whose support made the production of this document possible. In particular, we would like to thank the Charles Darwin Foundation, the University San Francisco de Quito, North Carolina State University and CIIFEN (Centro Internacional para la Investigación del Fenómeno de El Niño).

This study would not have been possible without the kind support and contribution of Abga. Marcela Aguiñaga, Ecuador Ministry of the Environment; the Ministry of Agriculture, Farming, Aquaculture and Fisheries; the Galápagos National Park Service; the acting Mayor of Puerto Ayora, Ing. Virgilio Santos; David Arana, Director of Agrocalidad-SICGAL; José Cajas Cadena, Agrocalidad; Commander Patricio Goyes, Director of INOCAR (Instituto Oceanográfico de la Armada); the Coffee Producers Association and Filemón Cueva; SENPLADES (Secretaría Nacional de Planificación y Desarrollo) and Camilo Martínez; National Institute of Galápagos (INGALA); Chamber of Tourism of Galápagos (CAPTURGAL); Stuart Banks, Charles Darwin Foundation; and Factor Verde.

We also express our gratitude to each of the workshop participants and their home institutions and to the numerous staff at CI and WWF that was involved in several stages of this project and the final workshop and provided feedback and input to several stages of the project. Particularly, we would like to thank Noémi d'Ozouville, Fernando Ortiz Quevedo, Free de Koning, Leah Bunce Karrer, Lee Hannah, Jeff Price, Mauricio Castrejón, Emily Pidgeon, Lauren Spurrier, Carolina Carrión and Emili Utreras.

Finally, Conservation International and WWF are grateful to their donors for their generosity which made this study possible.

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Acronyms

CAPTURGAL	Chamber of Tourism of Galápagos, acronym in Spanish
CDF	Charles Darwin Foundation
CI	Conservation International
CIIFEN	International Center for the Research of El Niño Phenomenon, acronym in Spanish
CIMEI	Inter-institutional Committee for the Control and Management of Introduced Species, acronym in Spanish.
CPUE	Catch per unit effort
EN	El Niño
ENSO	El Niño-Southern Oscillation
EUC	Equatorial Undercurrent
FCCC	United Nations Framework Convention on Climate Change
GAIAS	Galápagos Institute for the Arts and Science, University San Francisco de Quito
GMR	Galápagos Marine Reserve
GNP	Galápagos National Park
INGALA	National Institute of Galápagos, acronym in Spanish
INOCAR	Naval Oceanographic Institute, acronym in Spanish
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-tropical Convergence Zone
IUCN	International Union for Conservation of Nature
LN	La Niña
MMA	Marine Managed Area
MPA	Marine Protected Area
NGO	Non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
OAGCM	Ocean-atmosphere general circulation model
PDO	Pacific Decadal Oscillation
SENPLADES	Ecuadorian Secretary for Planning and Development, acronym in Spanish
SICGAL	Galápagos Inspection and Quarantine System, acronym in Spanish
SLP	Sea level pressure
SSH	Sea surface height
SST	Sea surface temperature
UN	United Nations
USFQ	University San Francisco de Quito
WWF	World Wildlife Fund


EUNICE PARK / WWF

Introduction

Giuseppe Di Carlo[1], Noémi d'Ozouville[4], Scott Henderson[3], Free de Koning[3], Irma Larrea[2], Fernando Ortiz[3], Emily Pidgeon[1], Lauren Spurrier[1] and Luis Suárez[3]

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The Galápagos Islands are renowned worldwide for their unique biological diversity. Located in the Eastern Tropical Pacific, 600 miles west of the coast of Ecuador in South America, the Galápagos Islands lie at the confluence of both warm and cold ocean currents. Such conditions provide habitats for tropical species, such as corals and red-footed boobies, temperate species like sea lions and macro-algae (kelp), and cold water species such as penguins and fur seals. On land unique ecosystems have developed to adapt to either harsh arid conditions or variably wet conditions.

The extreme weather and ocean conditions brought to the region every 2-8 years by the El Niño phenomena, which are associated with high ocean temperatures, and torrential rainfall, mean that the species and habitats of the Galápagos Islands face cyclical climate shifts. For this reason, the Galápagos provides a globally-unique 'field laboratory' for assessing impacts of climate change on biodiversity.

Climate change is predicted to increase sea levels, change ocean temperatures and alter oceanic currents around the Islands, and change the amount and distribution of rainfall. Acting together with current human influence and pressure on the natural ecosystems, all of these effects will result in accelerated species losses. The loss of the Galápagos biodiversity will directly impact the local communities as their livelihoods are primarily tourism, fisheries, and agriculture, all of which are dependent on these threatened natural resources.

To ensure the long-term survival of the biodiversity and the people of the Galápagos, it is essential to understand the vulnerability of this region to climate change and to define the urgent priority actions we must take to face these challenges.

In July 2008, growing awareness of climate change in the Eastern Tropical Pacific and potential impacts on Galápagos ecosystems and human well-being, especially combined with growing pressure on the natural systems, compelled WWF, Conservation International (CI), and the Charles Darwin Foundation (CDF), in partnership with the Ecuador Ministry of Environment and Galápagos National Park (GNP), to initiate a climate change vulnerability assessment of the Galápagos Islands. In September 2008, a preliminary meeting was held in Galápagos to begin the vulnerability assessment planning process, including the review of existing data on the effects of climate change on the Galápagos ecosystem and the services they provide for human well-being. Within the following months, research was conducted to integrate existing and new data to fill in knowledge gaps. Simultaneously, CI and WWF engaged local stakeholders and developed an effective strategy to create buy in and mainstream the outcomes of the vulnerability assessment. This process culminated in the vulnerability assessment expert workshop held in April 2009 in Puerto Ayora, Galápagos. At the workshop, local, national and international experts, scientists and decision makers reviewed the existing data, integrated data across disciplines and provided recommendations and priority actions for the next steps in ensuring Galápagos can adapt to the impacts of climate change.

The objectives of the vulnerability assessment were:

- To determine the potential impacts of climate change on the biodiversity and related human welfare of the Galápagos;
- To provide recommendations for management that addresses these impacts;
- To build in-country support for addressing the impacts of climate;
- To provide working examples of adaptation for the Eastern Pacific.

Vulnerability Assessment Expert Workshop 2009

Five keynote presentations were presented during the first morning of the workshop with a participation of over 150 people including local schools, naturalist guides, local NGOs and institutions. Expert presentations ranged from describing known climate change impacts in the Eastern Tropical Pacific to climate change modeling and analysis of current trends in oceanographic data. Key presentations about predicted impacts of climate change on marine and terrestrial biodiversity and the vulnerability of the local Galápagos community were also presented.

During the second day of the workshop 60 participants split in four working groups to discuss in detail about physical oceanography, terrestrial impacts, marine biodiversity and socio-economic impacts. Results from each working group were presented and discussed in plenary sessions. Also, a representative from the Ecuadorian Secretary for Planning and Development (SENPLADES) made a keynote presentation explaining the national framework within which adaptation plans and climate change-related programs should be developed.

On the last day of the workshop, a special round table was created to discuss with key authorities and stakeholders preliminary results and recommendations from the workshop. The round table was attended by the Minister of Environment of Ecuador, the Director of the Galápagos National Park, the acting Mayor of Puerto Ayora, the Director of Agrocalidad-SICGAL, the Director of INOCAR and a representative of the Coffee Producers Association. Each one of them also presented their views on climate change and its relationship with their institutions and its activities.

Key Recommendations for Adapting to Climate Change Impacts

The extent of losses to the diversity of life in the Galápagos, and, in turn, to the people who depend on those resources, will depend on how quickly and strategically the islands prepare for the coming changes. As climate change has already altered the balance of the oceans with serious and irreversible consequences for marine ecosystems and the services they provide, it becomes imperative to take actions to increase the adaptive capacity of coastal marine ecosystems and the people that depend on them. Adapting to climate change is the only solution to ensure ecosystems and human societies can survive and maintain their well-being when exposed to climate change impacts. Adaptation planning in the Galápagos should consider the following broad principles that reflect the unique economic and ecological conditions in the Islands.

Protect especially vulnerable species and ecosystems

Strengthen management measures to reduce existing pressures on marine resources, increase ecosystem resilience and integrate the management of coastal marine resources and continental protected areas with that of Galápagos. Protect climate vulnerable species, such as those that depend on the coastal zone for nesting and breeding.

Protect emblematic species to sustain tourism

Species such as giant tortoises, Galápagos penguins, and blue-footed boobies draw tourists that not only support thousands of Galápagos families, but also help fund local governments and conservation work in the islands. Protecting these species with actions that address the specific threats each face would have far-reaching economic and conservation benefits.

Strengthen the quarantine system to limit the introduction of invasive species

Regulate cargo access from the mainland to limit introduction of pests and invasive species. Adopt clean-cargo protocols in ports that service the islands, and develop better procedures to detect and respond to pests on arriving vessels.

Improve management of coastal and offshore-water fisheries

Improve management of fisheries and establish offshore no-take zones to anticipate shifts in fishing pressure as climate change will induce coastal fish stocks to move away from coastal waters due to increase in ocean temperature and increasing fishing pressure.

Promote climate research and establish climate-response monitoring protocols

Establish a monitoring and early warning system to detect the impacts of climate change on the ecosystems and species of the Galápagos. Promote research to fill in gaps on how species and ecosystems may respond to climate change and to enable managers to take adaptation actions.

Adopt a sustainable eco-tourism approach and coastal development

Promote the use of freshwater conservation, waste management and boat operations to avoid loss of species (sea turtles) and habitat (e.g. mangroves, coral reefs). Implement guidelines and best practices for coastal and foreshore development planning that take into account the potential for increased storm activity, salt water intrusion, and other climate change impacts. Improve and retrofit existing infrastructure to make sure they can sustain climate impacts.

Improve education opportunities and promote community awareness

Education and awareness are key strategies to increase language and communication capacity that will enable people in the Galápagos to occupy jobs in the tourism and service sectors or by providing credit lines to allow a shift from coastal to offshore fishing, which requires sturdier, better-equipped boats. Outreach programs can help create awareness and engage communities on climate.

The workshop concluded with the signature of the Declaration of Santa Cruz, where the Government of Ecuador, represented by the Minister of the Environment, together with partners and all participants agreed to support and invest in future climate change research for Galápagos and on the need to translate the recommendations proposed during the workshop into adaptive management actions to protect the Galápagos biodiversity and the islands' communities. (See Annexes I and II)

The present publication aims to support efforts to tackle climate change in the Galápagos and use the recommendations and priority actions from the workshop to implement an adaptation plan for the islands, and work toward increasing the resilience and adaptability of Galápagos in view of the uncertain future climatic changes.


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CHAPTER 1

Climate and Oceanography of the Galápagos in the 21st Century: Expected Changes and Research Needs

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ABSTRACT

With the expectation that levels of carbon dioxide and other greenhouse gases in the atmosphere will continue to increase for the next several decades, and that the planet as a whole likely will warm as a result, we expect the oceanography and climate of the Galápagos to change. Based on the analysis of observational studies and climate models, we expect the following primary changes in the Galápagos in the coming decades: (1) warmer sea surface temperatures, (2) continued El Niño and La Niña events, some of which will be intense, (3) a rise in sea level of several centimeters, (4) increased precipitation, (5) lower surface ocean pH, and (6) a reduction in upwelling. These changes in the oceanography and climate will likely alter the marine and terrestrial ecosystems of the Galápagos in ways that are difficult to predict.

Major uncertainties exist concerning the relationship between the expected changes in ocean temperatures, upwelling, seawater pH, and precipitation on the regional scale that most climate models consider, and the local scale of the Galápagos Islands that was the central focus of this study.

1. TEMPERATURE CHANGE

There has been no discernible trend in sea surface temperature (SST) in the region of the Galápagos (a 2° x 2° grid box, or about 200 x 200 km on a side, centered on 0°N, 90°W) since the start of the Industrial Revolution (the last 127 years; figure 1a), the end of World War II (the last 62 years; figure 1b), or since 1981 (the last 26 years; figure 1c) (Smith et al. 2008). Nor has there been any trend in local SSTs at Santa Cruz Island in the Galápagos over the last 44 years (Trueman, Hannah and D'Ozouville, chapter two in the current volume). Yet the larger equatorial Pacific, as indicated by the Niño 3 index of SST in the region 90°W—150°W and 5°S—5°N, has warmed 0.4°—0.8°C over the last 40 years (IPCC, 2007b), and warming throughout the region is expected to continue over the course of the 21st century, with the best estimates indicating 1°—3°C of additional warming (IPCC, 2007b). Whether local SSTs in the Galápagos will continue to buck the warming trend observed in the greater equatorial Pacific region over the last 40 years is unknown. But it seems imprudent to extrapolate from a failure to follow the regional temperature trend when that trend is only 0.4°—0.8°C, and conclude that local sea surface temperatures (SSTs) will not rise in the face of the expected 1°—3°C of warming in the equatorial Pacific region this century.

Additionally, despite the overall trend towards warmer SST in the equatorial Pacific, decadal variability very likely will continue, but this variability may well be stochastic, and there is a large consensus that its spectral character is very red (Gedalof et al. 2002). One of the most prominent decadal variations, the Pacific Decadal Oscillation (PDO) is not necessarily a forcing, and could simply be the result of El Niño-Southern Oscillation (ENSO) (Newman et al. 2003).

A lack of understanding of the linkage of large spatial scale analyses (e.g. IPCC-type) to the local scale of the Galápagos remains, and addressing this gap should serve as the focus for future research questions. There is a clear need for more meteorological and hydrographic observations, combined with widespread data archiving, so existing time series of SST and meteorological conditions can be made available. One

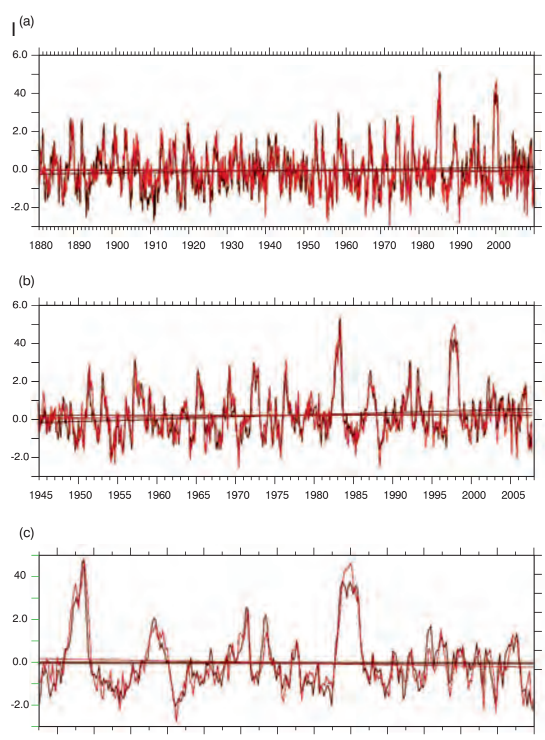

Figure 1: Monthly mean SST at 0°N, 90°W for the periods (a) 1880-2007, (b) 1945-2007, (c) 1981-2007. Data in black are derived from NOAA's historical merged SST analysis (Smith et al. 2008), and the data in red are derived from the Hadley Center's global analysis of SST (Rayner et al. 2003). Linear least squares trends are plotted for both time series, and both time series are referenced to have zero mean over the plotting interval.

step toward achieving this aim would be to reinstate the radiosonde program in the Galápagos.

Additional research should focus on continuing and expanding down-scaling model experiments, specifically by including more ensemble members and exploring methods for down-scaling atmospheric models. It is important that the ocean-dynamics community be enlisted to help answer these questions.

Paleoclimate records are another tool that can be used to link large spatial-scale analyses to the local scale of the Galápagos. Future research should focus on generating new paleoclimate records, especially from the lowlands, and linking these records to extend instrumental records. Calibration of the paleoclimate proxies under modern conditions should be an integral part of the development of these records.

Finally, it is necessary that we develop a better understanding of dynamics and the interactions of both the Panama Current and the Humboldt Current with the Galápagos, a topic we revisit in Section 6.

2. EL NIÑO

ENSO is the dominant mode of global climate variability on an inter-annual time scale that strongly impacts the Galápagos (Cane 2005; Philander 1983). During El Niño events, the surface ocean around the Galápagos warms substantially and the islands receive significantly more rainfall than in normal years. The warmer water is less nutrient-enriched than the cool waters that normally surround the Galápagos and the marine ecosystem consequently becomes disrupted, with mass mortality of coral, seabirds, and marine mammals occurring during the strongest El Niño events, such as those in 1982-83 and 1997-98 (Glynn 1988). Major disruptions of terrestrial ecosystems also occur with rainy conditions permitting the establishment of new colonizing plants and animals, and dramatic increases in the biomass of herbaceous plants and vines at the expense of cacti (Holmgren et al. 2001).

Since 1880 A.D., El Niño events have occurred roughly every 2–7 years, with no clear periodicity (Philander and Fedorov 2003). The late 20th century was characterized by particularly strong and frequent El Niño events that led some researchers to conclude that an anomalous change had occurred in ENSO that could be attributed to increased levels of atmospheric greenhouse gases (IPCC 2001; IPCC 2007a; Trenberth and Hoar). This claim has been challenged by other researchers and at best is highly uncertain (Cane 2005; Rajagopalan et al. 1997). The duration of the instrumental record of SST and atmospheric pressure is simply too short to conclude that such a fundamental change in ENSO variability has occurred (Wunsch 1999). Though supported by some theory and models (Timmermann et al. 1999), a link between greenhouse-gas-induced global warming and increased frequency or intensity of El Niño events remains inconclusive (Collins 2000), with the average of projections from coupled ocean-atmosphere general circulation models showing no change in ENSO variability over the 21st century (Collins and Groups 2005; IPCC 2007b), but rather a tendency toward a more El Niño-like state in the tropical Pacific.

In all likelihood, ENSO-related climate variability will continue in the coming decades and is very likely to modulate SST, rainfall, and sea level changes in the Galápagos on inter-annual timescales (IPCC, 2007b).

Future research in this area should include continued efforts to understand the long-term behavior of ENSO by the global climate modeling community (this is a major research thrust by IPCC-related researchers and modelers). Additionally, it is necessary to develop ENSO indicators relevant to local conditions. For example, 2008 was characterized by very high rainfall amounts in the Galápagos even though it was not an El Niño year.

3. SEA LEVEL RISE

Global mean sea level has risen by about 20 cm since 1880 A.D. as a result of global warming (IPCC 2007b), and the rate of increase has accelerated since about 1930. However, the rate of sea level rise since the mid-20th century has not been as significant in the eastern equatorial Pacific as in other parts of the world ocean (IPCC 2007a). Locally, there has been no discernible trend in sea level over the last 26 years on Santa Cruz Island in the Galápagos (figure 2).

Nevertheless, global mean sea level is projected to rise by 20-50 cm (IPCC 2007b) or more (Rahmstorf et al. 2007; Solomon et al. 2009) over the 21st century and the Galápagos likely will be affected by the increase. Subsidence of some of the islands, or portions of the islands, in the Galápagos, has the potential to exacerbate the local rise in sea level in the coming decades.

Adaptation to sea level changes may be viewed through the lens of strong El Niño events, which cause sea level in the Galápagos to increase by up to 45 cm, as occurred during the 1997-98 El Niño-event. Recent land-use changes (e.g. coastal development) have made the Galápagos much more vulnerable to even modest rises in sea level, and to sea level rises associated with El Niño (Clarke and Van Gorder 1994; Clarke and Lebedev 1999).

Moving forward, it is important to determine why local sea level in the Galápagos has not been observed to rise in concert with sea level in the eastern equatorial Pacific, and to monitor local rates of subsidence that may exacerbate the rise in sea level associated with the global mean thermal expansion of the ocean. It would therefore be advanta-

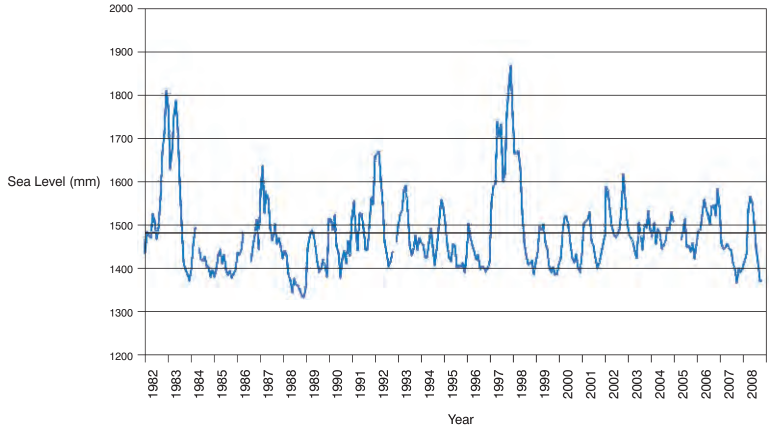

Figure 2:
Sea level at Santa Cruz from 1982-2008. No significant trend exists in the data. The two large El Niño events of 1982-83 and 1997-98 are clearly visible as periods of higher-than-normal sea level. Data available online from the University of Hawaii Sea Level Center http://uhslc.soest.hawaii.edu/

geous to augment the tide gauge on Santa Cruz with additional tide gauges throughout the archipelago.

4. PRECIPITATION AND *GARÚA*

Mean annual precipitation in Puerto Ayora, Santa Cruz Island, has varied significantly over the last 45 years, with El Niño years being characterized by high rainfall and La Niña years characterized by low rainfall (Trueman, Hannah and D'Ozouville, chapter two in the current volume). But this relationship can break down, as observed in 2008, a non-El Niño year, when rainfall amounts were greater than in several El Niño years of the last half century.

On longer time scales, our rainfall reconstruction from the sediments of Lake El Junco on San Cristobal Island indicate that the Galápagos have been trending toward a wetter mean climate since the start of the Industrial Revolution about 130 years ago (Sachs et al. 2009). The driest period of the last 1,200 years in the Galápagos was apparently the end of the 19th century, which we attribute to the end of the Northern Hemisphere climate anomaly known as the "Little Ice Age" (Grove 1988). Since that time, there has been a century-long trend toward wetter conditions, though even modern rainfall amounts are lower than at any other time in the 1,200 years prior to about 1880 A.D. Reconciling our paleoprecipitation data, which indicate increasing precipitation over the last several decades, with the observations for the last 45 years that indicate no significant trend in precipitation, is possible considering that the El Junco sediment samples average over 30 years of deposition, and there could be some differences in rainfall recorded at sea level on Santa Cruz Island and at 750 m on San Cristobal Island. Nevertheless, if the century-long trend toward a wetter climate in the Galápagos that is implied by the El Junco data continues, we would expect the Galápagos to receive increasing mean annual amounts of rainfall in the coming decades.

Whether the trend toward increased precipitation since the start of the Industrial Revolution is connected to anthropogenic alteration of the climate is unknown, but the IPCC indicates a greater than 90% chance of increased precipitation over the 21st century in the region of the Galápagos. As discussed for temperature, local changes will not necessarily follow regional changes, and a critical downscaling question concerns the trend of local Galápagos rainfall in the future. Much more extensive instrumental measurements of Galápagos weather (in both the highlands and the lowlands) needs to occur to address this question.

In addition to considering overall precipitation trends, it is necessary to assess the impact of a warming global climate on *garúa*, the dense fog that forms from low stratus clouds in the highlands, typically during the cool, dry season lasting from June to December. This water source is critical to highland plants and ecosystems. Future trends in *garúa* formation, duration, and elevation are uncertain because the physics of *garúa* formation are a complex function of SST, wind, and humidity. We surmise, however, that a weakening of the Walker circulation, as predicted by theory and many state-of-the-art global climate models (GCMs) (DiNezio et al. 2009; Vecchi and Soden 2007; Vecchi et al. 2006), would likely result in a reduction of *garúa* persistence in the Galápagos. In addition, if local SSTs increased, especially in the cool, dry season, the optical depth and/or seasonal duration of *garúa* would be expected to decrease. On the other hand, if the frequency and/or intensity of La Niña events increased or local upwelling increased, then an increase in the optical depth and/or seasonal duration of *garúa* might ensue.

Another complication is that, although it is tempting to use past El Niño events as a model for the influence of a warmer ocean on precipitation and *garúa* formation in the Galápagos, El Niño may not be a good model. The existence of a spatial pattern of SST in the tropical Pacific that is similar to that during an El Niño event does not necessarily imply that the underlying dynamics are the same (DiNezio et al. 2009; Vecchi and Wittenberg, in press).

Future studies should focus on understanding the dynamics of *garúa* formation. Specifically, it should be established whether there is a threshold SST above which *garúa* will not form, and what the influence of the large-scale ocean-atmosphere circulation is on *garúa* formation. It is possible that a better understanding of *garúa* formation could be achieved by analyzing existing precipitation, SST, humidity (both highland and lowland), pressure, and wind data to determine the conditions under which *garúa* forms and persists.

5. OCEAN ACIDIFICATION

An increase in atmospheric carbon dioxide (CO_2) levels from 290 to 385 ppm since the start of the Industrial Revolution has caused the ocean to become more acidic (Sabine et al. 2004). Consequently, global ocean pH ($= -\log_{10}[H^+]$) has declined by 0.1 units since 1880 A.D. and is expected to decrease by an additional 0.4 pH units by the end of this century (Caldeira and Wickett 2003). The increased acidity of seawater will make the production of calcium carbonate shells by marine plants and animals increasingly difficult (Orr et al. 2005). Making matters worse, regions where upwelling produces CO_2-rich surface

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water, such as the Galápagos, are more sensitive to increased CO_2 concentrations (measured in partial pressure of carbon dioxide [pCO_2]) (Doney et al. 2009; Manzello et al. 2008). This sensitivity is clearly demonstrated by the high buffer factor in the region of the Galápagos relative to most of the tropical and subtropical ocean, which indicates a decreased ability to buffer CO_2 changes (Sabine et al. 2004).

The upshot is that the calcifying organisms and the marine ecosystem in the Galápagos are likely to be more sensitive to an acidifying ocean as atmospheric CO_2 levels rise than the rest of the globe. When atmospheric CO_2 levels reach 450 ppm, which will likely occur by mid-century, coral growth is predicted to be at about 50% of its pre-industrial rate, due to a combination of higher SSTs and lower aragonite saturation levels (Fabry et al. 2008; Feely et al. 2008; Hoegh-Guldberg et al. 2007; Silverman et al. 2009). Coral reefs in the Galápagos likely will become incapable of surviving by the time atmospheric CO_2 levels reach 750 ppm (Silverman et al. 2009), the level expected by the end of the 21st century (IPCC 2007b).

Future study should address the relative vulnerability of Galápagos coral to ocean acidification, given that these corals already experience large swings in pH associated with ENSO.

6. UPWELLING

Changes in upwelling are the final impact of global warming on the Galápagos that we will consider. Reduced upwelling might be expected to result from weaker trade winds, which, in turn, weaken equatorial surface currents, reduce Ekman divergence, and reduce the east-west thermocline tilt, among other processes (DiNezio et al, 2009). Many of the most sophisticated coupled ocean-atmosphere GCMs predict a reduction in trade-wind strength, the Walker Circulation, surface currents, and vertical ocean velocity in the equatorial Pacific as a whole, and the eastern equatorial Pacific to a lesser extent, as atmospheric CO_2 levels rise (DiNezio et al. 2009; Vecchi and Soden 2007).

Unfortunately, it is difficult to discern what the changes in *local* upwelling in the Galápagos will be in the face of these large-scale changes in the circulations of the atmosphere and ocean. The upwelling that occurs in and around the Galápagos Islands results from a complex interplay between the bathymetry, the South Equatorial Current that flows west at the surface, and the Equatorial Undercurrent that flows east in the subsurface (Eden and Timmermann 2004). The archipelago presents a topographic barrier, disrupting the flow of these major currents and tropical instability waves, such as the Kelvin waves that are generated during El Niño and La Niña events (Eden and Timmermann 2004).

Because the Galápagos are small when compared to the grid size of most general circulation models, and the processes that cause upwelling in the Galápagos are influenced by basin-wide (i.e., 10^4 km) features as well as very small scale bathymetric features (i.e., 10^0 km), it is not yet possible to predict how changes in the coupled ocean-atmosphere circulation will affect the Galápagos upwelling regime. It is therefore necessary to address the same downscaling issues that exist for temperature and precipitation in order to link large spatial-scale analyses of changes in ocean currents to the local scale of the Galápagos.

Other currents that affect the Galápagos are the Panama Current and the Humboldt Current. However, there are too few model studies to provide information as to how these currents are likely to change over the course of this century. Such studies should be included in future research.

7. CONCLUSIONS

Over the next several decades, the Galápagos should be prepared for a number of changes related to global warming. Although varying degrees of uncertainty exist for each topic addressed, the future of the Galápagos more likely than not includes continued El Niño and La Niña events, some of which may be intense; increases in sea level, precipitation, and surface ocean temperatures; and a decrease in surface ocean pH. However, many uncertainties and areas for future research remain, particularly concerning the relationship between local and regional SSTs, precipitation, upwelling, and ocean acidification.

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CHAPTER 2

Terrestrial Ecosystems in Galápagos: Potential Responses to Climate Change

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1. INTRODUCTION

The terrestrial ecosystems of Galápagos have evolved within the unique climate of the archipelago and are therefore susceptible to any changes in the climatic regime. Driven by ocean currents and winds, the climate is uncharacteristically cool for its equatorial position, has two distinct seasons, and is periodically subject to extreme events associated with the El Niño-Southern Oscillation (ENSO). There is some inherent resilience among terrestrial Galápagos organisms and communities due to the natural rainfall variability associated with ENSO events. However, ecosystem responses would be very different if there was a change to the baseline climatic conditions or to the frequency or intensity of very wet or very dry years, all of which are possible under global climate change. Two especially powerful El Niño events in 1982–83 and 1997–98, characterized by anomalous warming of sea surface temperature, air temperature, and extreme precipitation, did result in substantial impacts in the terrestrial ecosystems. These observations can help us understand the vulnerability of species and ecosystems to potential future changes to the climate in Galápagos.

In preparation for the Climate Change Vulnerability Analysis Workshop of April 2009, we drew together data from local climatic records and observations of terrestrial species' and communities' responses to previous climatic fluctuations including ENSO events. These were first steps to better understand how regional climate variability and background climate conditions have shaped the terrestrial communities of Galápagos, and that information is presented in sections 2 and 3 below. Drawing on these observed responses to previous ENSO events and input from workshop participants, we predicted ecosystem responses to possible changes in the frequency and/or intensity of El Niño and La Niña events, ambient global climate change, and changes to seasonality or intensity of precipitation. These predictions are presented in section 4 below. Finally, in section 5, we provide recommendations to guide mitigation and adaptation strategies to reduce the threats to terrestrial Galápagos communities.

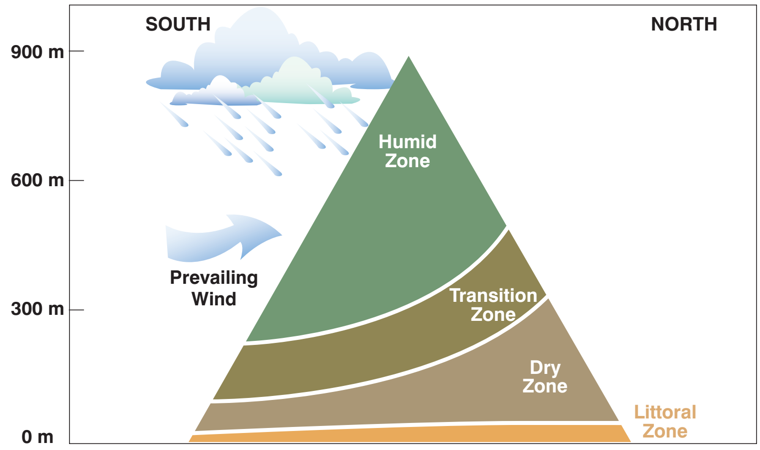
2. EXISTING GALÁPAGOS TERRESTRIAL CLIMATE

The Galápagos climate has been the subject of research and investigation for decades, as part of climate-related or biological investigations (Alpert 1963; Colinvaux 1972; Perry 1972; Newell 1973; Hamann 1979; Grant and Boag 1980; Pourrut 1985; Nieuwolt 1991; Huttel 1992; Snell and Rea 1999; d'Ozouville 2007). Trueman and d'Ozouville (2010) define the rainfall that occurs in two distinct seasons: The hot season, from January until May, is characterized by localized convective precipitation events, and total rainfall for the season is highly variable in relation to sea surface temperature. The cool season, from June to December, is commonly referred to as *garúa*, and is characterized by ground-level cloud cover, occult precipitation, and misty conditions in the highlands on the windward side of the islands.

Annual precipitation is generally lower on the coastal lowlands and higher on the inland volcanic mountains, particularly on south-facing slopes (Snell and Rea 1999). Anomalous high-rainfall years are usually associated with the higher sea surface temperatures and relaxation of trade winds associated with the El Niño phase of the ENSO cycle, occurring every two to seven years (Snell and Rea 1999). The La Niña phase of ENSO is associated with lower sea surface temperatures and lower rainfall. These ENSO effects are largely apparent in the hot season, although strong El Niño events have resulted in an extended period of convective rainfall, including some of the normal cool-season months. Years of high or low rainfall have occurred in isolation of ENSO events. For example, the hot season of 2008 experienced high rainfall, yet there was no El Niño event.

The spatial variation of rainfall in relation to altitude has resulted in a pattern of vegetation zonation (figure 1) from dry lowlands to humid highlands (Wiggins and Porter 1971). The dry lowlands (also referred to as the arid zone) occupy the majority of the archipelago, comprising nearly 83% of total land area (figure 2). The biodiversity in each

Figure 1. Galápagos vegetation zonation in relation to altitude.



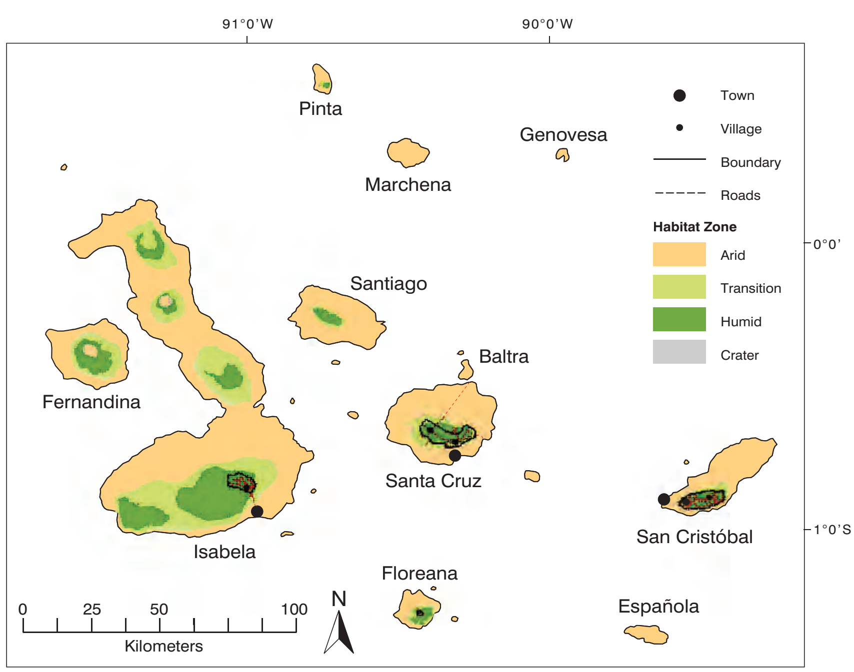
Source: Charles Darwin Foundation.

of the vegetation zones is adapted to the existing climate regime, and results in an uneven spread of endemic, native, and introduced plant species between the zones. The arid zone, characterized by exceptionally dry conditions punctuated by wet El Niño events, hosts the majority of the endemic plants in the archipelago (Porter 1979) and is not hospitable to the majority of introduced plants. The humid zone has higher biological productivity due to the regular rainfall it receives during the cool season every year. However, this zone is already significantly degraded on the four inhabited islands due to the combined impacts of land-use change and plant invasions (Watson et al 2009). Changes to the climate of the Galápagos, including changes to ENSO intensity or frequency, would have differing effects on each of the vegetation zones and the species within them. Therefore this report differentiates between the two major climatic zones: the dry lowland zone and the humid highland zone.

3. TERRESTRIAL BIOLOGICAL RESPONSES TO CLIMATE VARIABILITY

Scientists working in Galápagos, such as Hamann (1985) and Trillmich (1991), have recognized the utility of documenting Galápagos ecosystem responses to extreme climatic conditions as a predictor of potential climate change impacts. Unfortunately, very few experimental studies or monitoring programs have been conducted to document these effects. Useful observational information is provided by reports centered on the effects of the two severe El Niño events that occurred in 1982–83 and 1997–98 and a number of other publications. The following review describes observed impacts on Galápagos native vegetation, native fauna, and introduced species in both the arid lowlands and the humid highlands.

Figure 2. Map of Galápagos vegetation zones, principally derived from INGALA et al. (1989)



The effects of extreme climatic events on the Galápagos terrestrial environment are profound. In general, terrestrial organisms flourish during wet El Niño conditions and suffer through La Niña droughts (Snell and Rea 1999). On land, rainfall is the limiting factor to life. During El Niño conditions, southeast trade winds slacken, upwelling subsides, and raised sea surface temperatures generate higher rainfall on land. Jaksic (2001) summarized the terrestrial effect of wet El Niños nicely: there is a bottom-up system of ecosystem control, where more rainfall increases primary productivity, thereby increasing secondary productivity (e.g. insects) and tertiary productivity (e.g. hawks). In Galápagos, large increases in biotic growth have been observed during wet years, especially in short-lived species of plants and insects. Unfortunately, introduced terrestrial species also benefit from El Niño conditions in Galápagos, which has a negative impact on the native biodiversity (Snell and Rea 1999).

3.1. Arid-zone vegetation

The effects of El Niño events in the arid zone are pronounced, with a massive increase in herbaceous plant and vine abundance, an increase in overall plant diversity, and some increased mortality among several dominant, native species with longer life spans (Hamann 1985; Tye and Aldaz 1999). The overall species composition is not altered significantly, but El Niño events can alter community structure by changing the relative importance of the component species (Hamann 1985). Following El Niño events, a greater diversity of species has been recorded in long-term monitoring plots (Cayot 1985; Aldaz and Tye 1999) and records of species establishment show species in places where they previously have not been found (Luong and Toro 1985; Trillmich 1991). This potentially indicates the presence of a soil seed reserve of the emergent species. Also, in contrast to drier years, El Niño events create a dense herbaceous understory with vines and creepers covering higher vegetation (Tye and Aldaz 1999). In particular, the cactuses *Opuntia echios* and *Jasminocerus thouarsii*, the tree *Bursera graveolens*, and the shrub *Croton scoulerii* all had increased mortality due to falling over (due to being water logged) or being smothered in vines (Hamann 1985; Luong and Toro 1985; Tye and Aldaz 1999).

There also is a temporary alteration in growth and phenology among plants, including larger leaves, larger flowers, taller bushes, greater rate of growth, and longer retention of leaves in deciduous species (Tye and Aldaz 1999). Although no studies have quantified the increase in primary productivity or vegetation biomass during El Niño, anecdotal and photographic evidence indicates such increases would be several-fold as compared to drier years. A more localized effect of El Niño includes the erosion of all vegetation along newly formed watercourses (Tye and Aldaz 1999). Also, in areas previously degraded by goats, El Niño events assisted the recovery of some species (Hamann 1985).

Increases in the frequency of severe El Niño events could have negative consequences for longer-lived arid zone species that suffer under abnormally high precipitation. For example, *Opuntia echios* (prickly-pear cactus) and *Bursera graveolens* (palo santo tree) are two native, arid zone species characterized by high seedling mortality but exceptionally long life spans for individuals that survive into adulthood (Hamann 2001). Hamann (2004) suggests that the recruitment and survival of *O. echios* may be hindered if future El Niño events are more intense, with recovery periods for the cactus on the scale of 150 years, in accordance with the plant's life span.

Conversely, some species demonstrate a mass mobilization of the seed reserve (e.g. *Scalesia helleri*), and could thereby be positively affected by an increase in wet events, but negatively affected by more prolonged dry events. Trillmich (1991) proposed that many Galápagos plants only germinate, grow, and set a new seed reserve during El Niño events. In the arid zone, many species are adapted to prolonged dry periods by having a long-lived seed bank or mechanisms for water conservation. A rapid shift to a wetter climate could endanger these species by increasing competition from the vast majority of species that thrive in wetter conditions.

3.2. Humid-zone vegetation

There are significant effects of wet El Niño events in the humid highlands, but they are not as pronounced as effects in the arid zone (Hamann 1985; Luong and Toro 1985). Again, there is a massive increase in vegetation growth. In a long-term survey site within the humid zone initiated in 1970, Hamann (1985) reported an increase in the abundance of vines and herbs following the 1982–83 El Niño event. He also noted that diversity decreased, suggesting that some species were shaded out by faster growing, more dominant species. During the same period, Cayot (1985) observed how runoff, flow, and temporary water holes appeared to be very important determinants of the distribution of finer-scale vegetation communities in the transition zone. Tye and Aldaz (1999) also noted tremendous growth in ferns, herbs, grasses, and creepers, both native and introduced. During the 1997–98 El Niño event, there was an increase in the number of species recorded in permanent monitoring plots on Alcedo volcano: Prior to the event there were 60 species, compared with 100 species by the end of the event (Aldaz and Tye 1999).

One highland species that may be particularly affected by ENSO is *Scalesia pedunculata*. It exhibits a natural stand-level dieback and regeneration that appears to be linked with El Niño and La Niña events (Hamann 2001). Kastdalen (1982) first observed a decline in *S. pedunculata* trees in the late 1930's, followed by a subsequent regeneration in 1945, during rainfall following drought and disturbance by cattle and donkeys. Dieback in the species also was observed during the 1982–83 El Niño event (Hamann 1985; Itow 1988), with subsequent regeneration in 1985, again in response to rainfall following drought (Itow 1988; Hamann 2001). Hamann (2001) suggests that the short life expectancy of this and other *Scalesia* species makes them vulnerable to persistent, long-term disturbances. The stand-level dieback pattern renders *Scalesia* vulnerable to invasion by species with a more continuous growth and regeneration pattern (Tye and Aldaz 1999), which is particularly concerning as introduced plants spread through the archipelago.

3.3. Non-vascular plants

During the 1982–83 El Niño event, the lichen and bryophyte population was devastated in three ways (Weber and Beck 1985): destruction of habitats and substrates (e.g. tree mortality, scouring of rocks), effects on the plants themselves (e.g. lichen thallis damaged, individuals becoming waterlogged), and effects of differential competitive success of certain groups. In the highlands, a few dominant bryophytes dominated while rarer, smaller mosses and lichens were absent (Weber and Beck 1985). Ongoing work by Frank Bungartz has revealed many new species of lichens in Galápagos. The vulnerability of this group of plants to climate change is yet to be investigated.

3.4. Native terrestrial fauna

Tortoises

El Niño effects on Galápagos giant tortoises (*Geochelone nigra*) were observed during both the 1982–83 and 1997–98 events. During the former event, Cayot (1985) recorded little positive or negative effect, but observed the mass migration of a Santa Cruz Island population to lower elevations. During the 1997–98 event, observers documented increased mortality due to tortoises falling down ravines or drowning in floods (Snell and Rea 1999). Successful reproduction was also suppressed during the 1997–98 event for two reasons: (1) increased vegetation and wet soils reduced the temperature of the soil, rendering nests unviable, (2) hatchlings were attacked and killed by introduced fire ants (Snell and Rea 1999). Tortoise movements associated with El Niño events also are likely to assist the movement of plant propagules between lowland-coastal areas and highland areas (Trillmich 1991), and this could assist in the spread of alien plants as individuals find more favorable conditions in different environments. Current research is investigating the relationship between tortoise movements and environmental variables including ecology and climate. Results of this work will help explain how tortoise ecology might be affected by climate change (Stephen Blake, personal communication). Without this understanding it is difficult to implement adaptation measures.

Land birds

Many bird species in Galápagos are endemic and have small populations. As a result, they are at risk of extinction (Deem et al. 2008), especially in the face of introduced pathogens and disease vectors (Bataille et al. 2009). In general, bird breeding and bird populations respond positively to increases in biological productivity due to rain. Increases in mockingbird and finch breeding have been reported during El Niño events (Curry 1985; Grant and Grant 1999). Pathogens and parasites are affecting many bird species, and unfortunately these pathogens and parasites also tend to increase in wetter conditions. Curry (1985) reported that although breeding increased during the 1982–83 El Niño, there was no net increase in reproduction because they were negatively affected by pox at the same time. In particular, avian pox virus and the parasite *Philornis downsii* cause mortalities in many native and endemic bird species (Deem et al 2008). Introduced rats and mice also prey on birds. Wet conditions favor all of these introduced organisms. Recent unpublished research by Dale Clayton, Jody O'Connor, and Sabine Tebbich has shown almost zero recruitment among species of finches during the wet year of 2010, due to *P. downsii*, pox, and predation by rodents.

Sea birds

Seabirds on Galápagos and other islands in the region exhibit massive migrations and die-offs during El Niño events (Jaksic 2001) due to the fall in marine productivity and decrease in food availability. During the 1982–83 El Niño, all 15 sea bird species on Galápagos suffered species declines (Valle et al. 1987). Duffy (1989) reported adult mortality and nesting failure among penguins, flightless cormorants, waved albatross, greater frigate birds, brown pelicans, blue-footed boobies, masked boobies, swallow-tailed gulls, and lava gulls; and speculated that many birds dispersed and returned later. Waved albatross (*Phoebastria irrorata*) are likely to be negatively affected by a wetter climate because denser vegetation inhibits their ability to land and take off (Anderson et al. 2002).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The critically endangered Galápagos petrel (*Pterodroma phaeopygia*) is a seabird that nests under vegetation in the highlands of several islands and is therefore affected by the terrestrial environment as well as marine conditions. Nesting habitat is severely restricted by human activities and introduced species. Two of the major threatening processes are habitat alteration by invasive plants and predation by black rats, both of which are advantaged by wet conditions. Also, El Niño events have had a detrimental impact on nesting and productivity in the past (BirdLife International 2009). Many colonies are in stream beds, resulting in reduced breeding success due to flooding and debris deposition in wet years, which is compounded by the lack of food availability from the marine environment in El Niño conditions (Carolina Proaño, personal communication).

Reptiles and rodents

There is very little documented information on ENSO impacts on reptiles or rodents but evidence exists that certain reptile and rodent species are either reliant on annual rainfall or are advantaged by higher rainfall. Land iguanas (*Conolophus subcristatus*) are adapted to the seasonal variation and rely on annual rainfall for nesting and survival of young (Snell and Tracy 1985). Female lava lizards (*Microlophus delanonis*) that reproduced in times of low rainfall laid fewer and smaller eggs, and had lower post-laying body weight (Jordan and Snell 2002). In a 3-year study of the endemic rodent *Nesoryzomys swarthy*, Harris and Macdonald (2007) showed a positive correlation between rainfall, vegetation density, and body weight. The research also revealed an increase in breeding with higher rainfall.

Invertebrates

There are no published reports of direct effects of ENSO events on native invertebrates. However, anecdotal evidence suggests that enhanced vegetative productivity also benefits insects. Many more hawk moths and grasshoppers are observed in wetter years than in drier years. Roque-Albedo and Causton (1999) noted a secondary effect of El Niño events through introduced invertebrates. As introduced invertebrate populations increase, often coincident with El Niño events, the native populations are negatively affected.

3.5. Introduced and invasive species

Due to increased rainfall and productivity, El Niño events assist the establishment of new species in Galápagos by creating optimal conditions for reproduction, particularly in dry environments. Using examples of plants and birds, Trillmich (1991) explains, "El Niño rains increase the suitability of the habitat for a short while. This increases the chances of plants to find a permanently suitable habitat, and allows populations to escape from dangerously low levels to a size where the probability of extinction is low, even after the disturbance is low."

Since the two intense El Niño events of 1982–83 and 1997–98, invasive plants have continued to spread further throughout the archipelago, especially on the inhabited islands (Watson et al. 2009). Additionally, many species of introduced plants that are still restricted to the inhabited areas have been identified as future potential invaders (Guézou et al. 2010). It is expected that there will be more naturalizations and invasions from the existing introduced flora in Galápagos due to increasing residence time and growing human population and development (Trueman et al. In press.). Hence the risk of future invasion is already high, and this would be even higher with wetter conditions. Once established, introduced plants can be fierce competitors.

Vegetation

During the 1982–83 El Niño, Luong and Toro (1985) observed that several introduced plants were favored by the higher rainfall, including *Psidium guajava, Syzigium jambos*, *Pennisetum purpureum*, and *Caesalpinia bonduc*. Alternatively, Cayot (1985) observed that *Sida rhombifolia* expanded during that El Niño event, but that other introduced plants were not successful at invading native vegetation in the transition/*Scalesia* zone. Dispersion of introduced plants was also observed during the 1997–98 El Niño (Aldaz and Tye 1999). Species that spread noticeably included *Rubus niveus*, *Lantana camara*, *Ricinus communis*, and *Cinchona pubescens* (Tye and Aldaz 1999).

Vertebrates

Smooth-billed anis (*Crotophaga ani*) were introduced in the early 1960s, but remained rare until the El Niño of 1982–83 produced a population explosion over Santa Cruz and facilitated dispersal to other islands (Rosenberg et al. 1990; Trillmich 1991). They also increased greatly during the 1997–98 El Niño (Snell and Rea 1999). Introduced pigs and goats both increased with more available surface water during El Niño, and goats benefited from increased vegetation to eat (Campbell 1999). Efforts to eradicate these animals also were impeded by denser vegetation (Campbell 1999). Introduced frogs became established in Galápagos during the 1997–98 El Niño and these are the first known amphibians to reside in Galápagos (Snell and Rea 1999). Further wet conditions would facilitate the frogs' range expansion and potential impacts on biodiversity, such as effects on native invertebrate populations.

Invertebrates

Twenty-three percent of all Galápagos insects are introduced species (Causton et al. 2006). The islands most affected by introduced invertebrates are the central, inhabited islands, although introduced invertebrate species have spread to more remote islands during strong El Niño conditions (Roque-Albedo and Causton 1999). These conditions also have induced a spread in the two species of introduced fire ant. The spread of the fire ant has been associated with a drop in diversity of native species due to predation or stinging bird or reptile species (Roque-Albedo and Causton 1999; Lubin 1985). Future events may facilitate the dispersal of invertebrates to the more pristine islands with a higher diversity of habitats, such as Fernandina and Pinta (Roque-Albedo and Causton 1999). Some species, such as the wasp *Polistes versicolor*, are more positively affected by dry conditions, with population expansions recorded during strong La Niña events (Roque-Albedo and Causton 1999).

Parasites and pathogens

Wet conditions favor most parasites and pathogens, including mosquitoes that serve as vectors for disease. Avian pox and the parasitic fly *Philornis downsii* both have increased during El Niño events in Galápagos, negatively affecting bird reproduction (Dudaniec et al. 2007; Curry 1985). A shift to wetter conditions in Galápagos could lead to population explosions of species already present, facilitate their dispersal around the islands, and also facilitate the introduction of new species. Hotter conditions will allow certain species to increase their range, thus potentially threatening species that currently are not at risk. For example, West Nile virus is a mosquito-borne virus whose mosquito vector is already present in Galápagos. The virus is expected to reach Galápagos in the coming years, with rapid and dire outcomes predicted for endemic vertebrates (Bataille et al. 2009).

3.6. Summary

Workshop participants noted that published data on the effects of natural climate variation on Galápagos terrestrial biota is incomplete, and much of the available information is anecdotal. However, important themes emerge: Most native and introduced terrestrial organisms thrive during wet El Niño conditions and suffer through drier La Niña conditions. Many plant species appear to rely on periodic wet events for their life cycle, relying heavily on soil seed reserves that are germinated and replenished during these events. Several species seem to benefit temporarily from wetter El Niño conditions and therefore are able to expand their territory or out-compete species that are not similarly advantaged. This effect is more pronounced in arid-zone vegetation. Additionally, several important species appear to be negatively affected by wetter El Niño conditions, including *Opuntia* cactus, palo santo trees, and perhaps giant tortoises.

Although the native biota are adapted either to rely on or to cope with the temporary climatic variations linked with the ENSO cycle, a more sustained alteration in the local climate would have very different effects. Additionally, long-term trends in the general Galápagos climate or climate-change-induced perturbations to the frequency or severity of ENSO cycles may imperil native biota by facilitating a higher rate of alien species introduction or by expanding the suitable habitat of invasive species already present. The terrestrial-ecosystem working group formed during the Climate Change Vulnerability Analysis Workshop of April 2009 identified the potential for an enhanced threat of invasive species as an essential consideration for effective planning and management of the impacts of climate change on the Galápagos ecosystems.

4. POTENTIAL GALÁPAGOS TERRESTRIAL RESPONSES TO GLOBAL CLIMATE CHANGE

Workshop discussions concluded that the effects of global climate change in the Galápagos will include a continuation of ENSO events, some of which will be intense, and warming of the sea surface temperature with an associated increase in precipitation (Sachs and Ladd, Chapter 1, this publication).

Under current climate conditions, arid lowlands regularly go without much rain for several years but receive periodic wet years, and the humid highlands regularly receive rain every cool season. Participants agreed that maintenance of the arid zone is highly dependent on the continuation of this pattern of irregular hot-season rainfall, and maintenance of the humid zone is highly dependent on the continuation of cool-season rainfall. General local warming and resultant increased hot-season rainfall would likely mean that rain falls every year in the arid zone, es-

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sentially removing the aridity of that zone and thereby reducing the competitive advantage of the characteristic arid-adapted species that exist there and making it more favorable for invasive species. The combined effects of persistent wet conditions and the presence of invasive species would be catastrophic for arid-zone species, many of which are endemic to Galápagos.

Due to the naturally highly variable rainfall of Galápagos, there is inherent resilience in the terrestrial biodiversity

Table 1. Significant potential responses to climate change

Climate Change Scenario	**Humid zone**	**Arid zone**	**Vulnerable species**
Increased *garúa* duration and decreased convective activity and heat in the hot season	↑ Plant productivity ↑ Pathogens ↑ Invasibility	↓ Productivity Reptiles disadvantaged	Floreana mockingbird and other arid-zone passerines, mangrove finch, *Miconia robinsoniana* (light-limited), tortoises, iguanas and lizards, seed-bank-dependant plants in the arid zone
Decreased *garúa* duration and increased convective activity and heat in the hot season	↓ Productivity Aridification, ↓ Size of El Junco Lake ↑ Evaporation	↑ Productivity ↑ Evaporation	Species in El Junco Lake, *Miconia robinsoniana*
El Niño return-rate increase	↓System resilience Shift toward rainforest community structure. ↑ Invasive species and pathogens	↓ System resilience Shift toward rainforest community structure, Invasives and pathogens advantaged ↓ Tortoise nesting ↑ Invertebrate populations	Cactus, palo santo tree, reptiles
El Niño intensity increase	↑ Pathogens ↑ Continental invasives Impacts on vertebrate reproduction Negative impacts on *Scalesia* forest Reduced ocean-to-land nutrient transport	↑ Pathogens Invasives advantaged ↑ Erosion Reduced ocean-to-land nutrient transport	Lichens and bryophytes, *Opuntia* spp., highland *Scalesia* spp., mangrove finch
La Niña return-rate increase	↓ System resilience ↓ Pathogen transmission Vertebrate and invertebrate population declines ↑ Immuno-suppression	↑ Seabirds More male baby tortoises Reduced ability to hatch ↑ Competition for food ↓ Recruitment of plants Reptiles disadvantaged	*Calandrina*, *Lecocarpus*, Floreana mockingbird and other arid-zone passerines, seed-bank-dependant species in the arid zone, endemic snails, mangrove finch, reptiles
La Niña intensity increase	↓ System resilience ↓ Pathogen transmission Vertebrate and invertebrate population declines ↑ Immuno-suppression	Herbaceous plants disadvantaged Decreases in decomposition, soil formation, and nutrient cycling Create openings for invasives Reptiles disadvantaged	Floreana mockingbird and other arid-zone passerines, reptiles

to changes in rainfall. However, anthropogenic effects alter this resilience by interfering with ecological processes. In the Galápagos terrestrial environment, it seems apparent that invasive species are the human-induced agent that greatly increases the vulnerability of terrestrial biodiversity to future climate change.

The terrestrial-ecosystem working group developed a matrix to consider potential effects of long-term climatic shifts on the Galápagos ecosystem. The framework focused on changes to the duration of the cooler *garúa* season and changes to the intensity or return intervals of severe ENSO events. A summary of the working group's findings of significant potential ecosystem responses to each climate change scenario is presented in table 1. Potential ecological impacts are categorized into humid-zone and arid-zone responses as well as species that are particularly vulnerable to a certain climate scenario. The findings presented in table 1 are intended to portray representative directional responses to climate change to be used as a planning and management tool, rather than an exhaustive, quantitative document of all possible responses or impacts.

5. TERRESTRIAL-ECOSYSTEM WORKING GROUP RECOMMENDATIONS

The terrestrial-ecosystem working group developed recommendations for management actions that will help mitigate ongoing threats to vulnerable species and habitats, and minimize the impacts of future climate change. Broadly, the recommendations focus on: (1) limiting the impact of invasive species, (2) preserving intact habitat or restoring degraded native habitat, and (3) implementing land-use strategies that will help preserve and promote native biodiversity. An outline of the working group's recommendations, which could serve as guidelines in the development of robust, site-specific management policy, is presented below.

To achieve many of the recommendations, more information is needed regarding climate envelopes for vulnerable Galápagos habitats and species. This requires a better understanding of existing and past climate at a local scale that includes ecosystem complexity and changes along elevational gradients.

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Additionally, assessment of vulnerability and prioritization of management action require an enhanced knowledge of the current spatial distributions of threatened species, invasive species, and invertebrates—particularly disease vectors that could transmit pathogens to vulnerable native populations. The need for this additional research is recognized and is currently in development by the Charles Darwin Foundation, Conservation International, and other collaborating agencies. The working group recommendations were:

a. Prevent the introduction, establishment, and dispersion of new invasive species.

- Strengthen existing quarantine system with regulation and enforcement, and improve conditions of cargo boats and mainland ports.
- Strengthen the early-warning system for new invasive species and the rapid-response system for early eradication of newly introduced invasive species.
- Involve the local community through education and awareness campaigns.
- Continue to monitor and limit the pathways into Galápagos (e.g. limit ports of entry to Galápagos and ports of departure from mainland).

b. Reduce the impacts of established invasive species that would thrive under wetter, hotter conditions.

- Support and contribute to the long-term commitment to maintain the "Fondo para el Control de Especies Invasoras de Galápagos" (Control of Invasive Species Fund) and ensure its operability.
- Carry out systematic mapping and monitoring of spatial distribution and population dynamics of the species of highest threat potential.
- Strengthen institutional and inter-institutional capacity to enforce existing laws and regulations and to implement a rapid-response system that includes the community (e.g. municipalities, education institutions, and the "Comité Interinstitucional para el Control y Manejo de Especies Introducidas," CIMEI (Inter-institutional Committee for the Control and Management of Introduced Species).
- Prioritize the eradication or control of high-threat species in areas identified as vulnerable to or threatened by climate change (e.g. communities of high conservation value).

c. Reduce the threat of extinctions due to climate change.

- Identify and protect priority species and habitats identified as highly vulnerable to climate change or especially vulnerable due to other external pressures.
- Develop mechanisms to mitigate the impacts of climate change on priority species and habitats.
- Reduce external pressure on highly vulnerable species (e.g. control rats in petrel nesting colonies).

d. Restore ecosystem function and ecological connectivity to enable range and population shifts.

- Restore key biological communities, especially in humid highlands, through holistic methods that maximize ecosystem functioning and involve the strategic control of invasive species and reforestation.

- Protect native corridors and buffer zones along the altitudinal gradient on inhabited islands.
- Implement regulations and controls to minimize habitat fragmentation and allow native species to move across the landscape.

e. Improve agricultural productivity and land-use planning to create landscapes more resilient to change.

- Provide support for farmers to manage their land and reduce farm abandonment in order to reduce the spread of invasive species.
- Develop mechanisms to support the maintenance of native biodiversity within farms (e.g. agroforestry).
- Strengthen enforcement of laws or regulations to prevent removal or harvest of native species.

6. CONCLUSIONS

Globally, it is expected that climate change will greatly modify biodiversity and ecosystems (Holmgren et al. 2001). Workshop participants agreed that potential responses of the terrestrial biota in Galápagos to long-term global climate change could be anticipated using knowledge about biotic responses to past climatic variation and a range of future scenarios. In particular, a wetter, warmer climate is likely to lower the aridity of the extensive dry lowlands in Galápagos, thereby altering ecosystem structures and affecting endemic species. Systematic climatic and ecological monitoring will further enhance our understanding of biological responses to climate change and better enable us to assess the direction and speed of changes to Galápagos climate characteristics. Developing a framework of known biological responses to

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different types of climatic perturbations will allow us to anticipate ecological responses and identify species or communities that are especially vulnerable to the observed shifts in Galápagos climate. Finally, management actions that help minimize the impact of introduced species or economic land uses could potentially increase the resilience of endemic Galápagos species or communities under a changing climate.

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CHAPTER 3

A Review of Galápagos Marine Habitats and Ecological Processes under Climate Change Scenarios

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1. INTRODUCTION

Climate change is a global concern following post-industrialization since the mid nineteenth century. Excessive accumulated greenhouse gas emissions over a period when natural carbon sinks were removed through large scale deforestation and altered land use have instigated large scale shifts in the world's heat balance (Levitus et al. 2005, Orr et al. 2005, Raupach et al. 2007). Predictions into the next century suggest a range of consequences for biodiversity and resource availability (IPCC AR4 2007; Parmesan et al. 2003). Indeed, recent commissions such as the International Panel for Climate Change (IPCC) and UN Framework Convention on Climate Change (FCCC) have reviewed a preponderance of evidence from various science disciplines drawing the world's attention to documented signs of warming, associated degradation of ice shelves, sea level rise, changes in ocean circulation and ocean acidification (Soloman et al. 2008). While debate continues as to whether the contemporary rate of change exceeds that reconstructed over geological time scales from paleoclimatic records, evidence suggests that (1) gradual forcing and non-linear (chaotic) ENSO perturbations can trigger rapid climate shifts as certain physical thresholds are exceeded. This can cause feed-forward Bjerknes responses and rapid reorganization of the ocean-atmosphere system (Cane 2005; Zachos et al. 1993) and (2) that extinctions in ecosystems are more likely through increases in magnitude and frequency of climate events than through gradual shifts in climate (Edgar et al 2009; Reaser et al. 2000; Boer et al. 2004). Hence when assessing risk, we should consider that certain physical cues in the ocean-atmosphere system can trigger ecosystem tipping points that can significantly impact biodiversity and associated human wellbeing.

While present day greenhouse emissions continue to rise beyond low impact benchmarks (Elzen et al. 2005) the associated large scale environmental shifts (e.g. retreating glaciers, drops in recirculation of oceanic deep water into the euphotic zone, formation of anoxic submarine "dead zones," etc.) are expected to place new constraints upon both species distributions and resource demands by the human populace –particularly regarding the obvious interdependencies for ecosystem services such as fisheries, agriculture and non-extractive modalities such as nature based tourism (Stern 2008). The social, economic and political constraints associated with applying effective multinational greenhouse gas emission controls and mitigation measures have to date confounded a timely coordinated international response. The problem appears to have effectively outpaced the capacity of developed nations to disentangle the myriad interests and dependencies linked to changes in land use and dependence upon fossil fuels.

Due to the lagged response of accumulated heat transfer between the ocean and atmosphere, were anthropogenic aerosol emissions reduced we would still experience continued warming before stabilization over the next century (Meehl et al. 2005). Hence while governments address the very serious concern of reducing emissions and improving long term carbon sequestration, and individuals adopt lifestyles that reduce their carbon footprint, the onus has turned to adaptation. How can we quantify and then best confront the inevitable changes occurring across the biosphere into the foreseeable future and avoid large scale biodiversity to fiscal resource extinctions.

In terms of biodiversity management the relatively rapid rate at which change is occurring (compared to timeframes for selection processes) and the interruption of natural migratory pathways through global urbanization/ resource extraction, adds to a new suite of human pressures that include overfishing, maritime traffic and pollution. Patterns of human use interact with ecosystem resources in an often indirect fashion reducing natural resilience to extinction before climate events (Edgar et al. 2009). For example, barriers to pelagic stocks such as high extraction across industrial fishing grounds surrounding Marine Protected Area (MPA) refugia has potential to limit gene flow between meta-populations over 10 - 1000 Km meso-scales reducing genetic drift and population viability before adaptation pressures. Under heating stress at local scales (< 1 - 100 Km), reduced cold water refuge habitat, increased competition for a dwindling resource (such as anchovies feeding in reduced cold water upwelling cells around plankton blooms) and resulting mortalities can create genetic bottlenecks in populations. Increases in transoceanic marine traffic also can open new pathways for the invasion of novel species. Pathogens are more effectively transmitted as individuals retreat into smaller refuge habitat, overlap geographic living space and increase individual proximity. Concentrating climate sensitive species into smaller areas also increases the chance that a single perturbation event (such as anchor damage, disease outbreak, a directed fishery or an oil spill, etc.) results in mortalities from which populations cannot recover. The combination of such stress reduces potential for natural adaptation within and between generations favoring instead fast breeders, plastic specialists, or a subset of species that responds well to rapid niche shifts giving them a space or resource advantage over other species. Conversely it tends to exclude more specialist feeders with a limited foraging range –characteristics associated with many Galápagos endemics (e.g. marine iguanas, Galápagos penguins). It also implies that we should start to seriously rethink the appropriateness of existing management regimes in regions where environmental shifts reduce the representative protection or capacity for sustainable management of endangered species and resource stocks (Kareiva 2005).

There are still considerable challenges ahead to tease apart natural apparently stochastic climate variability and human driven changes. There are still sizeable gaps in our knowledge as to the mechanisms behind global ocean-atmosphere forcing and how natural background variability and anthropogenic drivers interact. At the Pacific basin level, a significant "regime shift" in ocean heat distribution reported over a few years in the 1970s has yet to be entirely understood. It may have represented either a tipping point in the operating mode of the ENSO climate system or decadal-scale variability (Graham 1994). Patterns in decadal cooling in the 1980s over the Pacific basin may also have masked residual background warming (MacDonald et al. 2005; Mantua and Hare 2002). Recent studies point to shifts in the ENSO mode – the predominance of the recently labelled "Modoki" El Niño for example where warm pool effects tend to extend into the tropical central Pacific but not into the Galápagos and eastern boundary current system (Yeh et al. 2009).

Considerably less is understood regarding the effect of such large basin scale shifts upon the complexities and peculiarities of circulation in smaller regions, despite differential heating being evident over the last 40 years across the world's oceans (Belkin 2009). Localities with varied oceanographic features already experiencing considerable regional climate variability such as Galápagos in the path of strong ENSO effects become important yardsticks to measure biological and societal response.

Attempting to estimate the resultant stress and threat posed to the many components and processes within the Galápagos ecosystem through periodic strong ENSO and anthropogenic (discrete or chronic) disturbances has been

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a recurring theme in local conservation science since the strong El Niños of 1976-77, 1982-83 and 1997-98. Those last two events coincided with the first systematic time series measures of Pacific basin oceanography (the TOA/TRITON buoy array (McPhadden et al. 2009)). The end of the 1997-98 event also saw the advent of synoptic satellite derived sea surface monitoring with unprecedented coverage in time and space. The pioneering NOAA-AVHRR/MCSST, NASA-SeaWiFS and later NASA-MODIS sensors captured admirably the spectacular variability and patterning of near-surface productivity and temperature.

Despite the anecdotal nature of many biological records at the time, researchers began to document *in-situ* observations. Amongst those, notable systematic studies include the rapid deterioration of bleached habitat forming coral frameworks by opportunistic bioeroder urchins (Glynn et al. 1979; Glynn et al. 1984). CDF Investigators in later years began to characterize complete subtidal communities (Danulat and Edgar Eds. 2002) and their accompanying oceanographic regimes (Banks 2002, Palacios et al. 2004, Schaeffer et al. 2008, Sweet et al. 2007, Sweet et al. 2009), documenting the collapse of overexploited benthic fisheries (Hearn et al. 2005, Toral-Granda 2005) while prioritizing threatened Galápagos species for additional protection.

Given both their importance in influencing marine community structure (as habitat forming species) and suspected recent extinctions linked to ENSO events, corals and marine algae were reviewed for inclusion in a new IUCN red listing —drawing attention to future extinction risk linked to climate change scenarios (Carpenter et al. 2008). Today 43 marine species are considered threatened under red listing criteria with at least 2 probable extinctions (marine algae *Bifurcia galapagensis* and damselfish *Azurina eupalama*), six possible extinctions of marine algae, and the sea star *Heliaster solaris*. Research continues to qualify how climate disturbance events coupled with human disturbance (such as extraction of resource species) might cause broad shifts in ecosystem composition and biodiversity state that inhibit natural recovery processes (Edgar et al. 2009).

These themes were discussed between local and invited international experts within a "Climate Change Vulnerability Analysis and Adaptation" workshop held on Santa Cruz Island 20th – 24th April 2009. To further climate debate and as part of a larger initiative for developing climate change adaptation measures for the Islands, we present a review of known climate related marine interactions for Galápagos.

2. METHODS

Given the ambiguity in current Ocean Atmosphere Global Climate Model (OAGCMs) predictions, the approach taken was to describe the level of potential risk given our understanding of past climate impacts in the Galápagos Marine Reserve (GMR). This exercise within expert working groups generated a suite of interpretations for use by managers towards precautionary measures while predictive models improve. The analysis was framed by (1) known effects of the considerable seasonal and El Niño-Southern Oscillation (ENSO) variability upon GMR marine habitats and processes, and (2) the extrapolated effect of a reasonably conservative global-climate-change scenario upon the GMR.

The first scenario drew together recent technical overviews, including Banks et al. (2009), Charles Darwin Foundation (CDF), Instituto Nacional Oceanográfico de la Armada (INOCAR), Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN) oceanographic and ecological data sets, contributions from participating experts during the Vulnerability Assessment workshop, and published literature documenting the last two large ENSO events. The review was targeted toward short- and mid-term adaptation solutions from 2010 to 2015. Under this scenario, ENSO continues to generate periodic strong El Niño (EN) and La Niña (LN) disturbance events as observed in the 50 years of recent GMR history.

The second scenario considers a suite of GMR effects associated with background global warming as defined by the IPCC AR4 SRES A1B emissions scenario (a future world of very rapid economic growth, low population growth, and rapid introduction of new and more efficient, low-emission technology). The inherent assumption was that global climate shifts will exacerbate or ameliorate natural GMR variability (including possible impacts upon ENSO intensity, periodicity, and frequency).

Where appropriate, boundary ranges for each physical climate variable were estimated for each of the two scenarios. These discussions often were accompanied by an estimate of "uncertainty in prediction" where information exists and were discussed in detail within a separate physical climate discussion group.

The effects of combinations of climate change effects and human stressors upon the GMR were analyzed under two time frames (2010-2015 and 2015-2050).

Where possible, inferences were substantiated through past observations and data. Where data was insufficient, a separate exercise identified future research needs.

Figure 1. Habitats, processes, and species interactions considered during the climate vulnerability discussions.

Category	Climate effects	Human stressors
Reef-forming coral communities	Increased temperatures (El Niño intensified and background warming)	Overfishing Introduced species
Cold water upwelling/ macroalgae dominated	Decreased temperatures (La Niña intensified) Indirect trophic impacts	Sea urchin dominance Habitat loss
Intertidal rocky reef	Change in meridional surface transport	Illegal fishing
Coastal biogeography	Reduced upwelling (drop in primary production)	Bycatch
Soft bottom sediments	Meridional deviation in EUC	Pollution (chronic and spills)
Mangroves	Ocean acidification	Physical abrasion
Sandy beaches	Sea level rise	Tourism visitation
Focal-species=level effects	Storm surge and erosion processes	Regulated fisheries extraction
Fisheries	Physiological tolerance	
Invasive-species risk	Change in ENSO and PDO frequency (interval for recovery)	

3. RESULTS AND DISCUSSION

During the meeting, physical climate experts agreed that ENSO climatic variability will continue almost certainly into the near future, although there was far less consensus as to the future ENSO dynamic. The outputs from those discussions frame the various climate change scenarios. We examined the range of implications for physical-state change upon natural systems, and identified two high-impact scenarios with great implication for Galápagos conservation: (1) El Niño and possibly La Niña events intensify as background temperatures increase, and (2) deep turnover of productive cold water to the surface is reduced (an intensification of ENSO thermocline depression in the Eastern Pacific).

The first part of the following section outlines a series of possible scenarios discussing what we might expect to change in the biophysical environment under a shifting climate. It includes considerations based upon past tendencies through observations in the region. The second section examines the implications of each scenario individually for the principal subtidal habitat types where data exists: coral communities, cold water macroalgae and rocky reef based systems, under two time frames. The first timeframe (2010-2015) reflects the current situation in Galápagos under ENSO variability. The second (2015-2050) considers that global climate change alters the local climate dynamic. Soft, bottom-sediment habitat and mangroves were determined to be data deficient and, although not included here, their importance is recognized for future baseline research. Finally, we include a brief overview of potential interaction effects with anthropogenic stressors.

3.1. Climate change scenarios (used to frame discussion of expected effects)

A. *Increased background temperatures*: Galápagos will experience a gradual shift toward a persistently warmer state, with elevated sea temperatures, reduced *garúa* mist formation, and probable higher annual rainfall. El Niño sea surface temperatures [SST] peaks will intensify under gradual SST background warming.)

Observations:

i. The last 40-year warming trend shows a 0.4–0.8°C increase over larger spatial scales in the El Niño 3.4 region to the west of Galápagos, yet near-neutral conditions within the archipelago possibly linked to local Equatorial Undercurrent (EUC) upwelling and reinforced Humboldt flow from the southeast.

ii. Sea surface temperature (SST) records in Academy Bay over the last 40 years show an overall neutral trend, although increasing maxima and decreasing minima over time indicate more pronounced seasonality and local ENSO peaks during that averaged period (Banks 2009; Wolff 2010).

iii. Past warming or cooling trends are better described by moving averages due to strong decadal variability in the Galápagos region.

iv. Mean 1–3°C global warming is very likely over the next century (IPCC 2007).

B. *A drop in turnover of productive, cold, upwelled water:* A potential drop of 25% in turnover of deep, nutrient-enriched water to the surface (IPCC 2007) affects lower trophic levels and results in bottom-up restructuring of subtidal communities.

Observations:

i. It is more than likely that the Equatorial Undercurrent (EUC) will deepen in the Eastern Tropical Pacific over the next several decades (Vecchi and Soden 2007, CIIFEN-INOCAR, unpublished data 2009).

ii. The threshold at which thermocline depression affects vertical nutrient flux (and consequently Galápagos natural systems) has yet to be determined. Ecological monitoring of subtidal communities in Feb–Mar 2010, for example, show that despite moderate EN surface conditions, and a strong "Modoki" El Niño (warm pool) in the central Pacific, the turnover of cold, deep water was still present as shallow as 10 m in northerly Wolf Island, with widespread productivity and large schools of juvenile fish.

C. *Shifts in ENSO and Pacific Decadal Oscillation (PDO) amplitude and frequency:* Shifts between positive and negative temperature and productive anomalies may become more abrupt and of increased magnitude over space and time. Thermal and nutrient deprivation stress intensifies over shorter periods with fewer apertures for natural recovery.

Observations:

i. Despite advances, model OAGCMs vary in their ability to simulate many aspects of ENSO and an ensemble model approach is suggested to examine concurrence in predicted frequency shifts.

ii. A first HyCoM 4 Km^2-resolution Galápagos circulation model forced by the AR4 A1B warming scenario (Xie et al. 2009) showed increased warming from 25–30 years into the model run. Future ENSO events had similar periods, while the PDO phase moderating ENSO intensity shifted into longer 16-year intervals. This model showed a greater than 90% correlation with observed data.

D. *Intensified "La-Niña like" upwelling (stronger periodic La Niña events):* Some models suggest that contrary to local warming a shift in the land-sea heat gradient will encourage alongshore trade winds, intensify wind-driven equatorial upwelling near eastern current boundary systems, and effectively dampen the effect of increased SST anomalies in the region (Cane 1997).

Observations:

i. The Ocean Thermostat model (Cane 1997) suggests that an increased zonal heat differential across the Pacific could reinforce alongshore trade winds and eastern-current-boundary-system upwelling along the Peru-Chile margin and offset warming effects in connected regions such as Galápagos.

ii. Galápagos SST records show a slight trend toward cooler cold seasonal temperatures over the last 40 years and warmer hot season maxima, implying that degree heating and cooling days between transitions (and hence rapid temperature shifts exerting stress) have increased despite maintaining a near-neutral 40 year mean.

iii. Positioning of the thermocline determining the nutrient loading of upwelled water is critical to provision of productive surface waters.

E. *Changes in mass transport of surface waters around the islands:* Changes in meridional surface transport, reduced upwelling and hence primary production and a meridional deviation in the positioning of the EUC would influence both productive regimes and connectivity across the GMR.

Observations:

i. Any external forced climate change in the ENSO mode that results in weakening of the Walker circulation has the potential to alter the larger circulation and water-mass signature of surface flow around the archipelago.

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F. *Sea level rise:* Storm surge and erosion processes increase differentially across exposed coastline with incursions most apparent during spring tides.

Observations:

i. Sea surface height (SSH) is not uniform across the archipelago and during strong ENSO events shows significant variability similar to levels expected over longer global climate change scales.

ii. Tidal range at about 2 meters in Galápagos is relatively low at the equator compared to other regions, with Galápagos being naturally in a depressed SSH region 20–40 cm below the Eastern Tropical Pacific regional average (Banks et al. 2009).

G. *Ocean acidification:* A combination of relatively young (less than 30 years) upwelled water, absorption of excess CO_2 in subtropical gyres, and capped outgassing as anthropogenic CO_2 increases promotes a relatively rapid increase of partial pressure of CO_2 (pCO_2) in equatorial surface waters and a reduction of pH compared to other regions.

Observations:

i. In the Galápagos, upwelled water has a naturally lower pH of pH 8.10–8.15 (INOCAR 2009) when compared to other non-upwelling regions.

ii. These pH levels produce higher bioerosion rates in calcareous species.

iii. According to Sabine et al. (2004), buffer factors (Revelle factors) in the Galápagos region are reasonably low, suggesting a certain capacity to buffer pCO_2 increases.

3.1.1. Habitat-level considerations: I. Reef-forming coral communities

Risk projection 2010-2015	**Risk projection 2015-2050**
ENSO continues as in the past with future strong warm and cold events.	*Global climate change influences natural variability.*
A. Increasing sea temperatures In general, heavy bleaching mortalities are expected as in previous strong EN events. Since the 1997–98 event resulted in 21% mortality, compared to the 97% estimated from the 1982–83 event, we might expect that populations of the dominant massive corals *Pavona* Sp. and *Porites lobata* be reduced back to a similar base survival threshold favoring species with heat resilient species-zooxanthellate clade associations. Temperature changes also are suspected to have affected associated abundance of burrowing mollusks (e.g. *Lithophagia* spp.), sponges, and other as-yet-undocumented reef in-fauna and cryptofauna involved in nutrient recycling. Extreme EN events may indirectly cause local extinctions of dependant species through bleaching of their sheltering colonies. Once weakened, coral habitat is further degraded by bioeroders. **B. A drop in turnover of upwelled water** As mixed autotrophs, corals are less affected by drops in phytoplankton productivity, yet still require nitrogen supplement from zooplankton feeding. However, without periodic incursions of cold water, associated species that respond to temperature can be affected. Population growth of macroinvertebrate bioeroders such as burrowing mollusks and urchins in combination with fisheries' removal of their natural predators (e.g. lobsters and reef fish) likely played a role in affecting coral health and corals' natural recovery between strong EN years. Persisting coral reefs are in northern zones receiving a reduced influence of upwelled EUC water. Populations of rare voracious coral predators such as *Acanthaster planci* in the northern islands currently may be restricted by such cold-water incursions. Periods of reduced upwelling probably have favored coral development around fringes of upwelling regions. Coral recruits probably would not have time to establish during 1–2 year warm events in otherwise cold upwelling zones given their slow growth rates, with the possible exception of sheltered, shallow, sun-heated bays.	**A. Increasing sea temperatures** As temperatures across the archipelago increase, spatial SST gradients between cold upwelled regions will become sharper and may homogenize completely during strong EN years, when cold upwelling is reduced or stops. As a result, stratification in the upper water column is likely to become stronger with reduced cold water mixing to the surface. This suggests fewer cold shocks in the future for Galápagos corals with less cold water reprieve during bleaching episodes. Disease may increase if vectors and pathogens positively respond to an increase in temperature (Harvell et al. 2002). Warm-water-tolerant corals will displace cold-water-tolerant species. Gradually increasing background temperatures may favor survival of some shallow-water corals such as *Porites* Sp. over species such as *Pocillopora damicornis, P.eydouxi, P.inflata, P.elegans, P.meandrina, Gardinoseris planulata* and *Pavona* Sp., which tend to suffer heating stress. Burrowing mollusks (e.g. *Lithophagia*) and sponges may proliferate. Reduced, fragmented populations become more susceptible to extirpation events caused by point pollution, anchor damage, and transmission of pathogens by marine fauna and diver contact. Declining coral health may result from proliferation of urchin bioeroders and changes in the bioeroders' depth zonation. (For example, *Diadema mexicana* urchins may displace *Eucidaris galapagensis*, or may migrate deeper across different coral strata if the thermocline deepens). Extreme rainfall events may increase sedimentation stress (Fabricus 2005). **B. A drop in turnover of upwelled water** The top- and low-end heat tolerances of coral species define part of the environmental envelope determining coral survival. A persistent decrease in cold upwelling would favor more widespread coral growth in previously inhospitable western and central regions, yet also would reduce the extent of cooler refuge and deep-water habitat from which repopulation has occurred in previous years in warmer parts of the archipelago to the north. Lower nutrient loading, less plankton, and hence clearer water both may exacerbate bleaching and may reduce other food sources for reef bioeroders (Highsmith 1981). Reef-associated fil-

C. Shifts in ENSO and PDO amplitude and frequency

Both the interval between strong ENSO events and the rate of change from ENSO SST maxima to minima greatly affect coral framework recovery as well as the state of bioerosion of the reef following strong events.

After extensive bleaching following the recent strong ENs, Glynn (2009) reports a seven-year period (2000–2007) of considerable regeneration in coral tissue and recruitment across one of the few surviving reef structures in Darwin Island after the 1982 EN. Most sexual propagation of new recruits appears restricted to the vicinity of surviving source populations (Glynn et al. 2009). The recent ENSO frequency observed since the 1970s suggests that new recruits have a minimum "grace period" to establish before a periodic strong bleaching event.

Since 2004, a degree of recovery also has been observed in some sites with less-intact frameworks across Floreana, such as Corona del Diablo and Bahía Gardner in Española, that prior to the 1982–83 EN event had high coral cover (CDF-Marine obs.).

D. Intensified "La Niña-like" upwelling

Temperature variability greatly influences local marine communities. A cold shock of 11°C at 10 m depth over just 6 days in Feb–Mar 2007 (associated with the passage of internal waves across the archipelago) caused widespread bleaching in Galápagos *Porites lobata* and *Pocillopora* Sp. corals from Wolf to Española Island (Banks et al. 2009). Whereas northerly corals recovered within the following month, the normal transition to the cold season at the same time exaggerated cold-water stress to coral colonies in the southeast of the archipelago resulting in high levels of pocilloporid bleaching into the shallows. Increased persistent productivity also may have had shading effects limiting coral development.

Some areas in the western islands (e.g. Punta Espinoza in Fernandina and Bahía Urvina in western Isabela) also show historical evidence of uplifted massive corals that persisted in protected shallow bays around cold upwelling zones (Dunbar et al. 1994). This suggests that although now conspicuously absent, at some point prior to the volcanic uplift in the 1950s, conditions were favorable to coral recruitment despite now being in a cold upwelling zone inhospitable to coral growth.

ter feeders may be limited by the associated drop in productive upwelling. If the thermocline is depressed with less vertical transport and mixing, there is less chance of larval flux from depth after strong warm events, possibly affecting local recruitment.

If a tropical-water environment prevails with reduced incursions of cold water, novel circumtropical species with Indo Pacific or Panamic affinities can establish themselves and extend into what was previously cold-water habitat. Nutrient deprivation and competition effects notwithstanding, there may be increasing shifts from transient EN visitors to resident Galápagos species in the long term.

C. Shifts in ENSO and PDO amplitude and frequency

If the frequency of strong, stressful ENSO events increases, we would expect reduced reef recovery over the shorter intervening periods and we would expect the opposite if intervals increase. Such recovery also is mitigated by the presence of keystone reef predatory fish and spiny lobster, and hence is susceptible to shifts in and over-extraction by local fisheries.

Although connectivity between tropical coastal coral communities and Galápagos may increase with increased flow from Panamic and Indo-Pacific provinces, it seems likely that many species would not survive the combination of background acidification, implicit heating stress, and regional-scale degradation of colonies which interrupts recruitment between potential source and sink regions.

The degree of recovery almost certainly will be moderated by other compounding effects from reef bioeroders, bioeroder population controls (or lack thereof), the state of appropriate settling substrate, and possible establishment of novel benthic competitors.

D. Intensified "La Niña-like" upwelling

An intensification of bathymetry-forced upwelling of cooler water within the archipelago or an intensification of westerly extension of the equatorial cold tongue and Peru coastal surface transport from upwelling regions along the South American coast actually offset background warming trends observed in other parts of the Pacific.

Since there is a tendency for a shallow, superheated surface layer under the equatorial sun, regular vertical migrations of the thermocline through tidal and Kelvin-wave propagation across shallow subtidal reef may increase the frequency of significant temperature shock and subsequent bleaching of *Porites* and Pocilloporid corals, favoring instead *Pavona* Sp. development in the northern islands.

E. Changes in mass transport of surface waters

In the current PDO phase, the influence of the Humboldt Current system is more pronounced (Martinez personal communication.). A lower probability of external recruitment from Cocos or other northeasterly sites may mean that recruitment during the last 10–20 years is mostly localized in Galápagos, and is therefore more susceptible to local processes.

Although potential exists for exogenous recruitment, most recovery since 1998 appears limited to areas around persisting fragmented reefs (Glynn et al. 2009). Possible recruitment may originate from colonies protected from warming in deeper water.

F. Sea level rise

Depending upon the state of ENSO-related bleaching, corals are sensitive to physical abrasion and sedimentation of sand over living reef during storm-surge events (Robinson 1985).

G. Ocean acidification

Recent acidification studies show that Galápagos coral reef communities are naturally exposed to the highest pCO_2 and lowest aragonite saturation (V_{arag}) documented for any coral reef environment to date. As such, Galápagos recently has been cited as an ocean acidification "hotspot" (Manzello et al. 2010).

Acidification stress may correlate with the high (~21%) incidence of coral malaise in the remaining fragmented populations in the north (Vera and Banks 2009).

E. Changes in mass transport of surface waters

Source-sink larval contributions may shift between other marine protected areas (MPAs) in the region, such as on the Ecuadorian coast or on Cocos or Malpelo Island, as both prevailing currents and possibly levels of relative protection through management change. Hence, while the importance of protecting existing Marine Managed Areas (MMAs) continues, new zones within larger MPA networks may shift to play an important part in bolstering regional marine resilience.

F. Sea level rise

Stronger or more frequent storm events would increase damage to species more adapted to low-energy shallows near the coast, favoring resistant species such as barnacles. Those lobate and encrusting species with a wider depth zonation would be more likely to avoid damaging effects. As sea level rises, there may be subtle shifts in vertical zonation of coral species commensurate with their respective light, wave-abrasion, and temperature tolerances.

G. Ocean acidification

Current 2010 partial CO_2 levels are at 389 ppm. Unless very drastic emission standards are adopted within 1–2 decades, levels likely will increase to 450 ppm, at which point coral growth is predicted to fall to about 50% of preindustrial levels.

Since naturally high-CO_2 reefs persist near the V_{arag} distributional threshold in Galápagos, they represent a "canary in the coal mine" for Pacific corals and are expected to be among the first and most affected by ocean acidification (Manzello et al. 2010). Weaker cementation will make corals more susceptible to bioerosion and physical abrasion, also restricting recruitment (Colgan 1990). Other calcifying benthos such as coralline algae otherwise supporting reef cohesion also will be affected.

3.1.2. Habitat-level considerations: II. Macroalgae-dominated cold water upwelling

Risk projection 2010-2015

ENSO continues as in the past with future strong warm and cold events.

A. Increasing background temperatures

Past observations saw widespread algae mortality during strong ENs, which led to restructuring of subtidal and intertidal communities including unique, equatorial deep-kelp (e.g., *Eisenia galapagensis*) habitat and suites of co-adapted invertebrate and fish species. Recent assessments have included at least six marine algae species (*Dictyota galapagensis, Spatoglossum schmittuu, Desmarestia tropica, Phycodrina elegans, Gracilaria skottsbergii*, and *Galaxaura barbata*) among the IUCN Red List because they fulfill threatened criteria. These species are considered possibly extinct, and one species of intertidal Galápagos stringweed (*Bifurcia galapagensis*) is probably extinct. Algae-specialist feeders such as marine iguanas are rapidly affected by the loss of algae.

B. A drop in turnover of upwelled water

Cold-water productive areas are well correlated with improved stock recovery of coastal finfish (e.g. *bacalao*, deep-water *mero*, *camotillo*, and *blanquillo* spawning aggregations) and show regular evidence of juveniles. These areas represent important green turtle foraging areas, nesting zones for threatened marine birds such as the Galápagos penguin and flightless cormorant, and temperature refuge for cold-water-adapted endemic invertebrates and fish. Periodic drops in upwelled deep water and subsequently effects on macroalgae habitat during the ENSO cycle have profoundly affected the Galápagos coastal ecosystem in observed recent history.

C. Shifts in ENSO and PDO amplitude and frequency

Occasional temperature shock of at least 11°C is not uncommon due to vertical thermocline migration across subtidal reefs causing differential levels of heat stress. This is particularly evident in the western part of the archipelago under regular influence of cool 14–18°C upwelling while surface waters still can reach 28–30°C in exceptional summer months. Recovery of macroalgae since the last strong EN in 1997–98 was most obvious around the sustained upwelling areas in Isabela and Fernandina and along the western shores of central islands, although various intertidal species have not been recorded since (see section "A" above), suggesting a significant loss of habitat-forming algae under current ENSO periodicity.

Risk projection 2015-2050

Global climate change influences natural variability.

A. Incrgeasing background temperatures

Most marine endemism is associated with the upwelling western region, which includes critically endangered solitary corals and algae species. Local extinction events are likely if cold-water refuge habitat becomes more spatially restricted. If the thermocline deepens on average in the near future, then "EN-like" limitations upon upwelling of nutrient-enriched deep water productivity likely will occur. That threshold, if crossed more frequently during seasonal and ENSO shifts, will emphasize extended nutrient-deprivation stress across the archipelago. Many other species-interaction effects are expected but not quantified, such as the risk from toxic dinoflagellates.

B. A drop in turnover of upwelled water

Reduced upwelling would have differential effects across the archipelago, reducing the habitat diversity afforded by cold, nutrient-rich water and limiting productivity across the islands. Algal nursery habitat would be affected, as well as global productivity, producing consequent multiple shifts in community state, which also includes fisheries- and tourism-objective species. Important foraging areas would shift to reflect the dwindling or alternative food and nesting resources instigating changes in species ranges and behaviors (e.g. penguins and marine turtles). Circumtropical or Indo-Pacific species would extend ranges into reduced upwelling areas as a result of competition effects generated by incursions of warmer water.

Since most marine endemism and Peruvian-Chilean species in the islands are associated with cold-water areas, biodiversity would decline, with probable species extinctions.

C. Shifts in ENSO and PDO amplitude and frequency

Shifts in the time and intensity of ENSO and PDO cycles imply changes in exposure to both favorable and inhospitable conditions. The response and recovery period of the algae species within these time frames can limit habitat development toward a more robust, mature associated community. Hence, openings develop for rapid colonists, some of which (such as invasive *Caulerpa* Sp.) are hugely prolific and rapidly displace other native species.

D. Intensified "La Niña-like" upwelling

During periods in which nutrient upwelling is reinforced, general positive impacts are observed within algae communities, expanding niche ranges for cold-water adapted species and consequently increasing system productivity. La Niña events generally strengthen recovery of cold-water-adapted endemics, including fish and invertebrate species assemblages associated with subtidal algae stands. Reef fish and grazers also tend to increase in biomass, with evidence of stock recovery for some commercial depredatory finfish such as *bacalao*.

E. Changes in mass transport of surface waters

A shift in upwelling and positioning of the oceanic front seems to change pelagic species distributions usually drawn to ephemeral productive upwelling zones in open waters. Not enough is understood locally to qualify how the shifts in currents affect pelagic species, although it is clear that seasonal changes in affluence from the temperate Humboldt and warm Panama systems influence near-coastal subtidal compositions and whitefish capture throughout the year.

F. Sea level rise

Temperature stress compounded with increased storm surge during strong EN events weakens algae cementation to substrate within the turbulent upper-subtidal and intertidal zone.

G. Ocean acidification

Upwelling areas tend to have naturally higher ambient pCO_2 levels due to the recent contribution of deep, lower-pH water into the surface layer. Although there is no local data to date, it can be hypothesized that western upwelling communities may exist at limiting pCO_2 thresholds for certain more-sensitive groups, such as calcareous algaes, in a similar way to corals. It is unclear whether in some cases native and endemic species have developed a level of natural resistance to acidification effects associated with freshly upwelled deep water.

D. Intensified "La-Niña-like" upwelling

If protracted, cold, La Niña conditions develop more frequently, populations may be bolstered between years by increasing ranges of intertidal and subtidal algae. Faster-growing temperate algae also may impinge upon ranges of tropical species and overgrow coral in transient upwelling areas. As long as cold, nutrient-rich upwelling is maintained, observations suggest that the coastal fringe may benefit under periodic surface warming interspersed with provision of deep water into the sunlit, mixed surface layer.

E. Changes in mass transport of surface waters

Meridional shifts in the EUC affecting its expression in the surface around the Islands may alter the position of cold-water refuge areas for some species of conservation importance (e.g. penguins) into possibly unprotected zones. If shifts in prevailing currents are pervasive, mobile species may concentrate in refuge pockets. Larger-scale shifts in predominant transport from Indo-Pacific, Panamic, or Humboldt provinces would reinforce respective connectivity with algal banks across these regions to Galápagos.

F. Sea level rise

Stronger or more-frequent storm events would increase damage to algae more adapted to low-energy, shallow water near the coast. In general, incremental sea level rise at the ranges suggested should not negatively affect macroalgae habitat above that observed periodically during strong spring-tide and surge episodes.

G. Ocean acidification

Phytoplankton coccolithophores and coralline algae are among those groups known to be affected by acidification (Riebesell et al 2000). Calcareous algae plays a role in reef cohesion and integrity across the archipelago, concreting reef frameworks during transitions between coral, algae, and barnacle habitat formers over ENSO and seasonal cycles. Observations around acidic ocean vents suggest that rich benthic assemblages can be rapidly replaced by tough sea grass and invasive algaes.

3.1.3. Habitat-level considerations: III. Intertidal and subtidal rocky reef

Risk projection 2010-2015	Risk projection 2015-2050
ENSO continues as in the past with future strong warm and cold events.	*Global climate change influences natural variability.*
A. Increasing background temperatures Rocky basaltic reef covers more than 80% of the subtidal coastal reserve and underpins the macroalgae and coralline communities described. Most rocky subtidal reef is characterized between the temperature tolerances across these two systems, ranging from ubiquitous encrusting coralline algae (such as *Lithothamia* Sp. and filamentous *Ulva* stands) to a rich assemblage of benthic taxa upon vertical walls and high-current sites. Elevated surface temperatures homogenize water masses during strong EN events, reducing the biophysical gradient and patterning usually sustained by cold-water upwelling, which otherwise generates cold-water, temperate, and tropical habitat. Intertidal rocky reef and mangrove systems also interact with invasive species in the coastal fringe. In addition to threats such as the cottony cushion scale insect (*Icerya purchasi*), unique flora and fauna associated with mangroves (such as the mangrove finch, *Camarhynchus heliobates*) are at risk from introduced rats, cats, dogs, fire ants, pigs, and the parasitic fruit fly *Philornis*, which can benefit from heavy EN rainfall and increased temperatures near the coast. **B. A drop in turnover of upwelled water** Upwelled productive zones correlate strongly with areas of high fisheries extraction. Such areas tend to be ephemeral, variable in magnitude (with the notable exception of constitutive production in western Isabela and Fernandina), and spatially consistent. The influence of cold-water zones clearly supports a subset of Galápagos biodiversity derived from Peruvian and Chilean provinces (e.g. cold-water endemics), and hence contributes considerably to the islands' distinct biogeography. **C. Shifts in ENSO and PDO amplitude and frequency** Seasonal variability is reasonably high in Galápagos with a 2–4°C anomaly every year that increases up to +/- 6°C during strong ENSO warm and cold events. This variability already causes range shifts in subtidal communities in space and over depth. The extreme ENSO events, however, demonstrated multiple cas-	**A. Increasing background temperatures** If background warming increases the seasonal signal, we might expect resident tropical species to establish themselves during the warm season, gradually becoming more-dominant components of the ecosystem and displacing cold-water-adapted species. Also, transient, novel tropical species may encroach upon previous cold-water zones as the biome shifts. Certain changes, such as tropical fish grazing, may introduce a new trophic state between functional groups. **B. A drop in turnover of upwelled water** If the cold-water biome in Galápagos is reduced to key refuge spots and possibly disappears, the result would be a loss of endemic and native species through competition, resource limitation, or physiological stress. Some species may develop new feeding behaviors and persist. Recent observations of Galápagos fur seals colonizing in Piura, Peru, suggest that some species may have the capacity to shift poleward to cooler waters. **C. Shifts in ENSO and PDO amplitude and frequency** If temperature shocks are severe, habitat modification in coral and algae nursery habitats will become more pronounced, affecting wider taxa and species. These changes open windows of opportunity for novel seaweeds and other invasives such as *Caulerpa* Sp., which is considered one of the world's worst biological invaders and already has been observed in Darwin Island, Punta Estrada, and Tortuga Bay in Santa Cruz (M. Vera pers. comm.). Recovery will be sensitive to the length of intervals between strong climatic impacts and will be dependent upon the life history and biology of, and the succession dynamic between, the various biotic and abiotic components. Shifts in species composition due to macro-scale shifts in temperature and productivity patterning generate a different ecological equilibrium, with different biodiversity and functional state. Abrupt changes in strong ENSO minima and maxima are likely to stress the less-tolerant and less-adaptable species groups. During these changes, the often-rapid increase in habitat engineers such as urchins is

cade effects from the bottom up, emphasizing the limiting role that primary production within these larger climate signals has upon local ecological function.

D. Intensified "La Niña-like" upwelling

Strong La Niña years such as 2007 with its associated enhanced upwelling benefited recovery and expansion of cold-water-adapted populations and breeding success of some species, such as *bacalao* and marine iguana. Green algae normally predominate in cold periods, perhaps recruiting from the subtidal reef. Rapid recruiters such as *Megabalanus* barnacles tend to show a strong positive response to the reduced temperatures and productive regime (Witman and Smith 2003).

E. Changes in mass transport of surface waters

Prevailing currents and water masses seem to influence recruitment patterns. Following the 1997–98 EN, monitoring data revealed a juvenile red spiny lobster stock that may have originated during reinforced connectivity from the western Pacific. Other transient tropical species establish themselves to differing degrees across the archipelago. For example, novel tropical species (such as butterfly fish, (*Chaetodon* Sp.), and Indo-Pacific *Naso* Sp. unicorn fish) temporarily recruited to northern coral reefs during past strong EN events.

F. Sea level rise

Coastline habitat experiences storm surge during strong EN events, with near-subtidal reefs particularly affected. Mangrove systems do not appear affected locally since changes are short lived. During EN extremes, sea level rises are of a similar magnitude to that predicted for other regions over much longer periods and differ in height across the archipelago, presumably as a function of bathymetry and local circulation.

G. Ocean acidification

To date, ocean acidification effects upon subtidal rocky reef communities are poorly understood. Although recent opportunistic measures in 2010 at several sites suggested pH values of 8.1–8.2, wider monitoring is required.

likely facilitated by processes such as changes in temperature regimes and increases in fishing pressure on their natural predators. An absence of predator control can lead to excessive herbivory.

D. Intensified "La Niña-like" upwelling

Nutrient availability promotes bottom-up development of higher trophic groups. Grazers benefit, and, barring unforeseen non-linear effects, reef predators would respond positively. Interestingly, observations during the hot EN peak of 2010 showed that despite positive SST anomalies, EUC upwelling continued, intermittently driven by internal waves into the coastal mixed zone. The combination of enriching pulses of cold, deep water into the surface and anomalous, elevated surface temperatures seemed to favor productivity in a fashion similar to mid-latitude spring blooms. Unusually abundant spawning aggregations of reef fish, a very high abundance of juvenile fish throughout the archipelago, the presence of large reef predators, and pelagic species congregating inshore were observed.

E. Changes in mass transport of surface waters

Changes in source-sink populations and connectivity between populations are difficult to predict without more fine-scale, current modeling and larval (particle) tracking models. However, we would expect broad-scale changes in biogeography and biodiversity with any change in residency of water masses around continental margins or islands prior to passage to Galápagos.

F. Sea level rise

A gradual incursion of saline water into coastal dunes and wetlands would change the coastal nesting habitat for many species, with greater impact upon endemics with restricted home ranges (e.g. penguins and cormorants).

Mangroves fulfill important protection and productive roles, buffering the coast from Pacific swells and forming protected bays that make them ideal nursery areas for many coastal and open-water species. We would expect mangroves to gradually shift upshore and inland as the coastline recedes. The degree of relocation of mangrove stands would depend upon the coastal profile and what currently is bordering existing mangrove areas. Assuming that novel biological invasions are not a problem, over time, mangrove cover will extend in some areas and retreat in others depending upon coastal topography, inclination, and patterns of seed dispersal.

	G. Ocean acidification If pCO_2 continues to rise in the future, we can expect widespread impacts upon invertebrate exoskeleton formation and larval development, and probable deformities in mollusk shells (Doney et al. 2009). Deeper species likely will be more susceptible, as pH changes are larger and growth rates often are slower in deeper water. A general weakening of calcifiers (e.g. mollusks, echinoderms, and coralline algaes) will undermine reef structures.

4. CLIMATE INTERACTIONS WITH ANTHROPOGENIC STRESSORS

Non-climatic stressors	Estimated climate-shift interactions and exacerbating effects
Overfishing	Edgar et al. (2009) suggest important correlations between the overfishing of medium-to-large-sized reef predators (such as *bacalao* serranids, snappers, and lobsters) with urchin overgrazing, which inhibits normal benthic recovery after thermal stress events. The implication is that without natural predator controls, rapid response grazers have a competitive advantage causing population booms and subsequent collapse to early benthic succession states once overgrazed. Although the urchin dynamic for the northern islands (*Diadema* dominance) seems different from the southern archipelago (*Tripnuestes/Lytechinus* dominance), the message seems to be that there are significant interactions with overfishing and grazing pressure. Coupled with acidification and weakening reef accretion and recovery, the outlook seems grim for existing corals and macroalgae, which have in recent years been largely replaced by extensive urchin barrens. *Pocillopora* coral species are among the hermatypic corals most affected to date. The shift in habitat-forming species implies changes in associated fauna and flora that cascade through the whole ecosystem, including a decline in total biomass and loss of the self-contained nutrient cycling normally found within a coral habitat. Sea urchin dominance is symptomatic of such a regime shift where habitat-forming species are rapidly eroded. Fundamental changes in species composition and abundance toward low-diversity "urchin barrens" are characterized by encrusting algae substrate rather than diverse coral and foliose algae assemblages. There also may be regulatory interactions between *bacalao* and intertidal herbivores, as well as between subtidal reef fish, lobsters and urchins. With the advent of pelagic fisheries, there is an accompanying increase in net fishing for bait fish that serve as prey for climate-impacted species such as marine birds. Mullet is the principal target species historically fished near certain sandy beaches, and currently are not overexploited. Excessive netting for bait would affect many other juvenile fish species, including keystone reef predators that depend upon protected productive habitats, and in turn repopulate the surrounding reef. Overfishing for sea cucumbers and lobsters is unlikely to worsen, since fisheries bottomed out several years ago, and lobster shows some signs of recovery in parts of the GMR. Fishing has increased for pelagic species such as wahoo and tuna, and also coastal fish such as *bacalao*, *mero*, and *salema*. The coastal species are most at risk from warming due to their association with cold-water productive inshore habitat. Chitons, octopus, and gastropods (*Nerita*) may be overfished near port zones as demand increases locally for seafood. Appropriate and regularly revised quota controls are key to improved resilience of fisheries stocks under a shifting climate.

Non-climatic stressors	Estimated climate-shift interactions and exacerbating effects
Introduced species	Marine invasive-species risk will increase with a shift in environmental conditions accompanied by a seemingly inevitable increase in transoceanic marine traffic. These should be considered separately from transient species from connected provinces that establish during extended warm or cold periods. A reduction in suspension feeders such as barnacles that proliferate in cold productive water would open space for invasion of novel species. Greater connectivity with marine traffic hubs such as Panama and the Indo West Pacific increases the possibility of more arrivals. The novel algae species *Giffordia mitchelliae* with a tropical/Panama distribution first recorded in 1982 overtaking intertidal habitat as temperature increased was also later observed during the 1997 El Niño altering the grazing dynamic (marine iguanas, crabs and intertidal fish) (Vinueza et al. 2006). A warmer climate may exclude some invasive species that affect mangroves, such as the cushiony cotton scale insect (*pulgón*). Algae such as *Caulerpa* Sp. appears to be well established in Tortuga Bay. Some rare *Acanthaster coralivore* seastars appear to establish periodically across reefs at Darwin, although may be native to the island with distributions possibly limited to incursions of cold upwelled water. Population explosions of swimming crabs were observed in previous ENSO events, yet were rapidly consumed by Galápagos fauna. More research is required in this area.
Habitat loss	Loss of habitat from coral bleaching and algae stress results in multiple cascading effects reducing functional group diversity of the marine space: nursery habitat is reduced, affecting a range of codependent species accompanied with a drop in local productivity. Anchor damage, which can destroy 100 years of coral growth in minutes, is exacerbated by high maritime traffic and site visitation. In multiuse port areas, there is a risk of habitat modification for urban development. Removal of mangroves would affect neighboring habitats and marine communities, as well as remove the mangroves' local nursery, protective and productive ecosystem function.
Illegal fishing	Illegal shark finning, still one of the most lucrative illegal activities in the GMR even at moderate levels can affect top-down control of ecosystem function, given sharks' regulatory trophic role, low fecundity, and relatively long period to reach sexual maturity. Climate-shift effects may alter their distributions outside of well patrolled areas. Fishing outside of established quotas will in general exacerbate the aforementioned overfishing effects.
Bycatch	The collection of chitons across intertidal beaches close to port areas disturbs other species. Seafood other than the fisheries objective species is often served in local dishes such as *ceviche* and may vary as resources change with climate.
Pollution (chronic & spills)	With more spills and accidents every year, pollution is an ongoing concern in port areas, with contamination localized around anchorages. Rare corals such as *Gardinoseris* and *Pavona duedeni* are found in the bay area of Puerto Ayora, for example where they are susceptible to pollution. Tourism anchorages in protected bays with restricted circulation may alter the oxygen environment where coliforms accumulate, while small spills lead to bacterial and heavy metal accumulation in sediments. Chlorine use in tidepools although illegal is practiced around port zones mainly targeting octopus but affecting other marine life. Pollution encourages a monopoly by more-resistant species, building up within soft sediments over long periods, altering interstitial meiofauna and subsequently macrofauna. Mangrove areas tend to collect plastic and organic rubbish and accumulate light hydrocarbons from the frequent small spills from visiting boats.

Non-climatic stressors	Estimated climate-shift interactions and exacerbating effects
Physical abrasion	Diver and anchor damage can cause physical abrasion. Diver damage is more likely in high-current areas where divers look for handholds. Mangroves protect coastal zones from surge erosion and are relatively resistant compared to other biogenic habitats. Coral reefs that once afforded protection from along-shore erosion are largely absent since the 1982–83 EN event.
Tourist visitation	Inappropriate (high) levels of dive tourism and anchorage over coral reefs can exacerbate the impact of a suite of climate stressors (e.g. heat and acidification). Visitors also may inadvertently transmit coral disease and parasites between colonies simply by touching reef frameworks. Sunblock washing off tourists over time at a site also may affect reefs. Rocky reef systems are likely more resilient than coral reefs to direct tourism impacts, yet impacts will depend upon effective management of site quotas. As tourism develops, there is the risk that tour operators will search for underutilized, and often more secluded and pristine, areas such as Cabo Douglas, which are important reference and climate impact recovery areas with very little human influence and great biodiversity value. Some concerns exist for trampling effects upon iguana nests in well visited sites. Any overloading of tourism sites may change the behaviors and residency of intertidal keystone species. If erosion patterns change, marine access to terrestrial sites will need to adapt. Urban development driven by tourism puts demand upon sand as a construction material.
Regulated fisheries extraction	Benthic near-shore fisheries are mostly associated with the cold, productive up welling areas. If upwellling decreases, fisheries focus may shift by necessity to open-water alternatives requiring careful foresight and planning to encourage healthy long term stock harvest as resources and markets change.

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CHAPTER 4

Galápagos Marine Vertebrates: Responses to Environmental Variability and Potential Impacts of Climate Change

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1. INTRODUCTION

1.1. Vertebrate Diversity

The Galápagos marine vertebrates constitute a diverse group of species that includes marine iguanas, sea turtles, seabirds, sea lions, dolphins, and whales. (Teleost fishes and sharks are not considered in this report). Several of these species rely on coastal ecosystems, and even spend substantial portions of their time ashore, whereas others have an entirely aquatic existence and normally are found far from land. As major consumers of secondary and tertiary productivity, most marine vertebrates are widely regarded as the ocean's top predators, with the exception of marine iguanas and green turtles which feed almost exclusively on vegetation. Perhaps the most distinctive feature that the marine vertebrates of the Galápagos have in common is that they are among the most charismatic fauna of the archipelago.

Globally, climate change is expected to have deleterious impacts on marine vertebrates, primarily through food shortages and physiological impairment (secondary and tertiary impacts are also expected but less understood). However, quantifying, or even describing at a basic level, how climate change will affect the Galápagos marine vertebrates is a tall order. This stems from 1) our limited and fragmented knowledge of the ecology of the species, 2) a lack of adequate local-scale, spatio-temporally resolved climate change scenarios, and 3) the fact that climate change is expected to be a unidirectional, progressive process with no past analog on which to base predictions. The purpose of the present report is to provide an overview of known or observed responses to environmental variability, which could inform future responses to changes in environmental conditions driven by climatic change.

1.2. Biogeographic Affinities

The archipelago is divided into three biogeographic zones—the western, central-southern, and northern regions—which are determined by their location and degree of exposure to prevailing currents and water masses. Not surprisingly, the marine vertebrates of the Galápagos display distinct distribution patterns within these regions. Given that the predicted impacts of climate change include the alteration of oceanic currents (notably the Equatorial Undercurrent that fuels an elevated marine productivity in the Galápagos), consideration of present biogeographic affinities will be useful in predicting the impact of these changes on the Galápagos fauna. The green sea turtle (*Chelonia mydas agassizi*) is predominantly found in the western region (where most nesting occurs between December and May), as well as in the central-southern region. Marine iguanas (*Amblirhynchus cristatus*) occur throughout the archipelago, but their highest densities are found in the western region. The Galápagos sea lion (*Zalophus wollebaeki*) also occurs throughout the archipelago, but the largest colonies are found in the central-southern region. In contrast, the major breeding colonies of the Galápagos fur seal (*Arctocephalus galapagoensis*) are found in the western and northern regions.

More than a dozen species of seabirds make their home on different islands of the Galápagos, which they use for breeding and as a base for launching their ocean-going foraging trips. While the magnificent frigatebird (*Fregata magnificens*), the blue-footed booby (*Sula nebouxii*), and the brown pelican (*Pelecanus occidentalis urinator*) are ubiquitous throughout the archipelago, most seabirds have more region-specific distributions. The western region is host to 100% of the flightless cormorant (*Nannopterum harrisi*) and 90% of the Galápagos penguin (*Spheniscus mendiculus*) populations. In the central-southern region, Española Island hosts the largest concentration of Nazca boobies (*Sula granti*) and waved albatrosses (*Phoebastria irrorata*), while Santa Cruz Island is home to the lava gull (*Larus fuliginosus*). The Galápagos petrel (*Pterodroma phaeophygia*) nests primarily on San Cristóbal, Santa Cruz, Santiago, and Floreana Islands, while the swallow-tailed gull (*Creagrus furcatus*) nests on Plazas and Española Islands. The northern region is home to the red-footed booby (*Sula sula*), the great frigatebird (*Fregata minor*), the swallow-tailed gull, and two species of storm petrel (*Oceanodroma tethys* and *Oceanites gracilis*). The sooty tern (*Onychoprion fuscatus*) also nests on the northern islands of Darwin and Wolf.

A diverse cetacean community inhabits Galápagos waters, including several resident species and long-distance migrants such as the humpback whale (*Megaptera novaeangliae*) and the blue whale (*Balaenoptera musculus*). Among the residents, the short-beaked common dolphin (*Delphinus delphis*), the striped dolphin (*Stenella coeruleoalba*), the Risso's dolphin (*Grampus griseus*), the short-finned pilot whale (*Globicephala macrorhynchus*), the sperm whale (*Physeter macrocephalus*), the killer whale (*Orcinus orca*), and the Bryde's whale (*Balaenoptera edeni*) are predominantly found in the upwelling-modified waters of the western and the central-southern regions. In contrast, the pantropical spotted dolphin (*Stenella attenuata*) and the spinner dolphin (*Stenella longirostris*) are the predominant species in the warm and stratified waters of the northern region. The bottlenose dolphin (*Tursiops truncatus*) is common in nearshore waters of all three regions.

2. RESPONSES TO ENVIRONMENTAL VARIABILITY

In spite of being located on the equator, the Eastern Tropical Pacific undergoes marked seasonal changes driven by the annual north-south migration of the Intertropical Convergence Zone (ITCZ) and its associated trade winds. In addition, every four to seven years this region is affected by more dramatic changes caused by the El Niño-Southern Oscillation (ENSO) and its two phases: El Niño, with associated anomalously warm conditions, and La Niña, with cooler-than-normal conditions. As long-lived organisms, marine vertebrates are adapted to cope with these variations, although some species are more successful than others. Some species' responses to ENSO variability are illustrated below, as their responses to ENSO events are the best information available for understanding how species might respond to climate-induced changes. We know much less about how other environmental factors related to climate change will affect Galápagos marine vertebrates, but we provide brief discussions about their presumed impact where relevant.

2.1. El Niño

Green sea turtles and marine iguanas

Turtles and marine iguanas are primarily affected by the reduction in the amount of algae of the genuses *Ulva*, *Spermothamnium*, and *Centroceras*, which are their main food, and their food's replacement by inedible species or less palatable genuses such as *Giffordia* and *Enteromorpha*. Consumption of undigestible brown algae is one of the leading causes of mortality. During the last strong El Niño of 1997-98 the population of marine iguanas suffered 90% mortality. El Niño also affects reproduction and recruitment. Lower numbers of females arrive at the nesting beaches during these events, as nutritional stress may limit in their ability to perform long migrations. In addition, extreme high air and ground temperatures during incubation may cause feminization or death of embryos during development. Nest flooding and beach erosion caused by elevated sea level during El Niño also can have an impact in subsequent-year cohorts.

Sea lions

Severe reductions of up to 50% of the total population have occurred during strong El Niño events. During these events, up to 90% of the pups and 67% of the alpha males have died. Widespread movements, probably in search of food, have been recorded between islands and even to the South American mainland. Feeding habits are also significantly altered. Lantern fishes (*Myctophidae*) and serranids replace the South American pilchard (*Sardinops sagax*) as the main prey items, implying a switch to nocturnal and coastal foraging. The population can take up 10 years to recover after strong events. In 2005 the population was estimated at 18,000 to 20,000 individuals and appeared to be increasing. An expansion in the distribution range is expected in future warming events.

Fur seals

Less data on the effects of El Niño are available for fur seals, but the data are expected to be similar to those recorded for the sea lions, perhaps with less dramatic mortality. Like the sea lions, fur seals appear to range widely during El Niño events, as evidenced by movements to mainland South and Central America and even into the Gulf of California. The population also appears to be increasing from the strong events in the 1980s and 1990s, with numbers estimated at 8,000 to 10,000 individuals in 2005. Similar to sea lions, an expansion in the distribution range is expected in future warming events.

Penguins, cormorants, and other seabirds

Mortalities of up to 77% in penguins and 50% in cormorants were recorded during the strong El Niño events of 1982-83 and 1997-98. Breeding success is known to be lower in both species during weak El Niño events. Boobies, frigatebirds, and albatrosses show low reproductive rates and increased migrations outside the Galápagos Marine Reserve, while most young pelicans starve during El Niño events. One seabird species appears to benefit from El Niño: the wide availability of carrion results in an enhanced reproductive output in the lava gull. However, an increased abundance of migratory gulls arriving in the Galápagos during El Niño events may lead to competition with the endemic lava gull. Seabirds of the Galápagos also are negatively affected by the increased abundance of introduced, land-based predators (e.g. rats and cats) and disease vectors during El Niño events.

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Cetaceans

As highly migratory species, cetaceans are able to redistribute quickly in response to events such as El Niño. The reduction or collapse of the Equatorial Undercurrent coupled with decreased winds during El Niño results in the shrinking of the upwelling habitat in the western region. This in turn may lead to increased competition for food among the dolphin species that are dependent on this habitat. Warm-water species not normally found close to the islands might be more common during these episodes. Species such as sperm, Bryde's, and blue whales, which depend on the productive Galápagos ecosystems, may experience decreased foraging success during an El Niño year and decreased reproductive success in subsequent years.

2.2. La Niña

For most marine vertebrates, the La Niña phenomenon represents a favorable period of resource abundance, particularly in the western upwelling area. The cold waters bring nutrients and increased prey resources. For marine iguanas and sea turtles, the bloom of green algae provides sufficient food for adults and young individuals. The main limiting factor for these poikilothermic (cold-blooded) organisms during La Niña events is thermoregulation. For sea lions, fur seals, penguins, and cormorants, this is a perfect time to breed and increase in numbers.

2.3. Transient events

There is scant information regarding transient events such as upwelling Kelvin waves at the end of an El Niño, but it is presumed that sudden drastic reductions in water temperature on the order of 5–10°C over a few days, as occurs during the passage of upwelling Kelvin waves at the end of an El Niño event, may induce thermal shock and undermine the health of poikilothermic marine vertebrates.

2.4. Acidification

At present, we do not know the direct impacts of acidification. However, acidification seems to affect plankton abundance and distribution. Acidification also could affect the abundance of mollusks, crustaceans, and bony fishes, which constitute important prey for marine vertebrates.

2.5. Thermocline

The general prediction under climate change scenarios is that the thermocline will deepen and become more stratified. A deepened thermocline would reduce access to food resources for vertebrate predators, which are shallow divers. For instance, adult marine iguanas have been recorded feeding on algae up to depths of 12 m, while 90% of dives by Galápagos penguins and cormorants are conducted in water less than 6 m and 15 m deep, respectively. Galápagos fur seals get their prey at 10 to 35 m, while sea lions dive to an average depth of 115 m. Presently, the Galápagos thermocline is situated at between 10 and 20 m depth. If the thermocline were to deepen, the shallow divers are expected to be physiologically affected, and may possibly starve. Changes in foraging behavior also are expected, such as predators shifting to different prey.

2.6. Surges and extreme tides

Storm surges and extreme tides are infrequent under present conditions, as they are tied to earthquakes and volcanic eruptions. Surges and extreme tides also occur during El Niño because sea level is higher during these events. The effects of surges and extreme tides on the coastal areas will depend on the magnitude of the surge, the area affected, and the time of year. These three factors will have to coincide to generate a major impact at specific areas important for marine vertebrates (e.g. nesting areas of sea turtles, penguins, cormorants, and marine iguanas); and pupping locations for sea lions and fur seals. There are records of nest losses in penguins and cormorants by flooding during extreme tides and surges.

2.7. Sea temperature

The marked seasonal variation in sea temperature probably acts as an important factor in the synchronization and initiation of breeding seasons to match the availability of food resources. The prediction under climate change scenarios is for increased sea temperature, which may affect the breeding seasonality, in addition to reducing prey abundance and availability.

2.8. Air temperature

The effects of air temperature are unknown for most marine vertebrates. However, the lower temperatures of shady areas such as lava tubes and large boulders appear to be important for nesting penguins and resting fur seals. The normal variation of air temperatures seems at present fairly well tolerated by Galápagos marine vertebrates. However, extreme high air temperatures could result in increased stress and energy demands on species that need to thermoregulate while on land, such as marine iguanas, sea lions, fur seals, and seabirds. Dehydration could be another problem during high temperatures in tropical environments. Disease vectors, such as insects, also may increase in abundance due to rising temperatures on land and in the water, raising the risk of disease transmission. Disease outbreaks that resulted in a high morbidity (but low mortality) of sea lions were recorded in 2001 and 2006, mostly affecting the pups. The eye-disease (conjunctivitis and parasitosis) outbreak of 2001 has subsided, but these diseases persist today at a lower prevalence. High air temperatures also can generate a favorable environment for the breeding of introduced mosquitoes, such as the vector of avian malaria (*Culex quinquefasciatus*), and affect the endangered Galápagos penguin.

2.9. Upwelling

The upwelling areas in the western part of the archipelago provide reliable feeding conditions for marine vertebrates such as cormorants, penguins, sea lions, fur seals, and cetaceans. However, as this upwelling diminishes in intensity in a future warmer climate, these habitats will deteriorate and the marine vertebrate species that inhabit them will become vulnerable.

2.10. Sea level rise

At present, there is no clear evidence of an increase in sea level in the Galápagos. If this happens in the future, coastal flooding could impact breeding colonies for beach nesting species, erosion of nesting, pupping, and resting areas caused by coastal erosional processes. Sea level rise also could lead to a relocation of the breeding colonies or an increase in competition for breeding habitat in sea lions, fur seals, and seabirds.

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2.11. Precipitation

The amount of precipitation varies by season: Most rain falls in the hot rainy season (late December to April) and less in the cool dry season (May to early December). This pattern changes during El Niño and La Niña events, when the rainy and dry seasons are extended, respectively. Climate models predict a more extreme climate, with warmer El Niño events and attenuated (less cool) La Niña events. Sustained levels of humidity and fresh water could trigger a higher prevalence of disease vectors, parasites, and associated diseases or increased predation by introduced mammals such as cats and rats, which are predicted to become more abundant as prey resources increase.

2.12. Winds and ocean currents

Changes in wind directions and strengths likely will result in changes in ocean currents, precipitation, and thermal regime, which probably will affect the duration of the seasons as well as the synchronization of the breeding season for most marine vertebrates.

2.13. Native and introduced predators

In general, during warm years predation from sharks on Galápagos marine vertebrates appears to increase, especially from unusual visitors of these waters such as bull and mako sharks (Vargas, pers. obs.), probably in response to a reduced food supply. Populations of land birds such as finches and Galápagos hawks generally benefit from an overabundance of food during El Niño events. An increased hawk population could result in higher predation rates on young marine iguanas, penguins, and cormorants. In fact, young marine iguanas constitute an important prey item of hawks on coastal Fernandina Island (HV pers. obs.). Populations of introduced predators such as cats and rats also increase during El Niño years, when they tend to target the eggs and young of iguanas, penguins, and cormorants. Therefore, increased predation rates from both native and introduced species are expected to occur in a future warmer climate.

2.14. Parasites and diseases

Several new disease strains and parasite species have been recorded in the past ten years in Galápagos penguins, cormorants, and sea lions. Their prevalence appears to be closely associated with changes in the local climate. This situation is expected to worsen in a warmer, wetter climate-change scenario.

3. CURRENT AND FUTURE CLIMATE IMPACTS AND ADAPTATION MEASURES

Current and future climate changes indicate an overall negative impact on Galápagos marine vertebrates, with La Niña and the persistence of upwelling being the only events that probably have a positive effect on selected vertebrate populations (table 1). However, it is doubtful that extreme cold events, were they to occur, would have a beneficial effect on poikilothermic organisms such as sea turtles and marine iguanas. Climate models suggest that the current climatic conditions will prevail over the next 15 years, but the intensity of El Niño events will increase in the next 50 years (see outputs of Chapter 1), with a significant long-term negative effect on Galápagos marine vertebrates.

Based on current scientific and technological knowledge, it seems feasible to implement adaptation measures to counteract some of the impacts of El Niño events, extreme surge, air and sea temperature, sea level rise, and precipitation. Novel technologies and new scientific knowledge are required to counteract the current and future impacts of other climate factors (table 1). Adaptation measures are more feasible for vertebrates that spend a considerable amount of time on land.

4. RESEARCH AGENDA FOR THE DESIGN OF ADAPTATION MEASURES

A research agenda should begin immediately to enable adaptation measures before the next El Niño event, which is likely to occur within the next four years. The following research should be conducted:

a. Determine thermal tolerances, energy budgets, and the duration of periods needed for population recovery after mass-mortality events.
b. Assess incubation temperatures of sea turtles to determine threshold temperatures to ensure the development of male individuals.
c. Determine the movements and dispersal of Galápagos marine vertebrates outside the Galápagos region during El Niño and other extreme climatic events to plan for conservation needs beyond the archipelago.
d. Describe patterns of intensity and wind direction in relation to ENSO events, which affect birds that depend on wind for their movements (e.g. albatrosses) or that can be exposed to nest failures by wind knocking down nests (e.g. mangrove finches). This study also will help predict the intensity and distribution of extreme surges.
e. Develop methodologies for the design of cavities and artificial substrates for nesting penguins and cormorants, and test their acceptance by the species.
f. Monitor and evaluate tested adaptation measures.
g. Design modeling studies and improve existing models on population trends of the species more vulnerable to climate change.
h. Assess the likelihood of competition between sardine fishermen and marine vertebrates that are natural predators of sardines. Design management actions to ban temporarily the capture of sardines as bait during El Niño, when food for marine vertebrates is limited, and propose alternative bait.

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Table 1. Present and future climate impacts on selected Galápagos marine vertebrates and the feasibility of implementation of adaptation measures.

Climate event	Period	Sea turtles	Marine iguanas	Sea lions and fur seals	Seabirds	Cetaceans	Adaptation measures
El Niño	Present	-	-	-	-	-	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
La Niña	Present	+	+	+	+	+	Feasible
	15 years	+	+	++	++	++	Feasible
	50 years	0	0	0	0	0	Feasible
Acidification	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?
Thermocline	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?
Extreme storm surge	Present	-	-	-	-	0	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
Sea surface temperature and ocean currents	Present	-	-	-	-	0	Not feasible
	15 years	--	-	-	-	0	?
	50 years	--	--	--	--	0	?
Air temperature	Present	-	-	-	-	0	Feasible
	15 years	-	-	-	-	0	Feasible
	50 years	--	--	--	--	0	Feasible
Upwelling	Present	+	+	+	+	+	Not feasible
	15 years	-	-	-	-	-	?
	50 years	--	--	--	--	--	?
Sea level rise	Present	0	0	0	0	0	Feasible
	15 years	0	0	0	0	0	Feasible
	50 years	-	-	-	-	0	Feasible
Rainfall	Present	-	-	-	-	0	Feasible
	15 years	0	0	0	0	0	Feasible
	50 years	0	0	0	0	0	Feasible
Wind	Present	0	0	0	0	0	Not feasible
	15 years	0	0	0	0	0	?
	50 years	0	0	0	0	0	?

Present Impacts
- = Reduction in local abundance, population size, or breeding success; unbalanced sex ratio.
+ = Increase in local abundance, population size, or breeding success; balanced sex ratio.
0 = Insufficient information to evaluate current impacts, or impacts not evident.

Future Impacts
-- = Significant reductions in biological parameters.
+ + = Significant positive effects on biological parameters.
0 = Insufficient information to evaluate future impacts.

Adaptation Measures
Feasible = With current knowledge and technology, it is possible to implement adaptation measures.
Not feasible = With current knowledge and technology, it appears unfeasible to implement adaptation measures.
? = With future scientific and technological knowledge, it may be feasible to implement adaptation measures.

i. Monitor the impact of tourist-boat lights on insects. Research the use of technological options that do not attract insects and prevent the transportation and introduction of insects among islands.
j. Produce vulnerability maps of nesting areas of marine iguanas, sea turtles, penguins, and cormorants to anticipate possible flooding during extreme surges.
k. Use flooding models under various scenarios of sea level rise to produce vulnerability maps that evaluate the potential loss of breeding-area quality.
l. Assess future scenarios of ocean-current shifts at the Galápagos regional scale, as these shifts could alter the ecosystems and habitat quality of marine vertebrates.

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CHAPTER 5

Dealing with Climate Change in the Galápagos: Adaptability of the Tourism and Fishing Sectors

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1. EXECUTIVE SUMMARY

Currently, an estimated 25,000 people live in the Galápagos Islands. They depend directly or indirectly on the ecosystem, which provides resources and supports the cultural services that increasingly form the basis of the local economy. By affecting key ecosystem processes and emblematic species, climate change could influence the wellbeing of all people who live in the islands.

In this study, we analyzed the potential impacts of climate change on tourism and fisheries:

a. While tourism in Galápagos has shifted from specialized nature tourists to generic nature tourists, nature remains the primary reason that tourists travel to the islands. Because tourists are drawn by a number of emblematic species, significant adverse effects on the tourism industry are expected if many emblematic species go extinct because of climate change. Tourism is critical to the Galápagos economy, employing a large and increasing proportion of residents. Loss of nature tourists would mean loss of the majority of international tourists, who spend more money, on average, than national tourists. A further negative effect of declining tourism is that tourism provides funds for conservation efforts, and loss of that funding may contribute to further declines in ecosystem health. However, people in the tourism sector appear to have a relatively strong capacity to adapt to climate change because of their transferable skills, including strong language and communication skills; high education levels; strong institutional and social networks to support them during hardship; generally solid financial resources; access to credit; and relatively high economic capital.

b. Fisheries are a small percentage of the Galápagos economy, accounting for less than 4% of gross product (Watkins and Cruz 2007) and 3.55% of employment, according to the Galápagos Census 2006. Therefore, any adverse effects on fisheries will have limited implications for the larger economy. However, people within the industry—especially those who fish for sea cucumber, spiny lobster, and coastal demersal fish—will be adversely affected. The fisheries sector has a moderately strong ability to adapt, with the advantages that fishermen have strong social and institutional support, access to some credit, and 90% of fishermen have alternative livelihoods. Vulnerabilities include relatively low levels of education, language skills, communication capacity, and existing financial resources.

We recommend the following steps to support tourism and fisheries in the face of climate change:

A. Enhance resiliency of species and habitats.

For tourism:

a. Protect the species that attract international tourists to the Galápagos (tortoises, sea turtles, marine iguanas, penguins, blue-footed boobies, sea lions, and land iguanas) and the ecosystems that support them.

b. Develop tourism business strategies to address the uncertainty surrounding climate change.

For fisheries:

a. Establish sustainable management measures for demersal fish. Improve conservation efforts for seamounts, mangroves, and other key areas.

b. Protect sea cucumber, spiny lobster, and demersal species from overfishing, as these species are the most vulnerable to climate change.

c. Establish sustainable management regulations for pelagic species that may not be heavily fished at present, but could become more important due to climate change.

B. Enhance people's adaptive capacity.

a. Promote diversification of livelihood activities, particularly within the tourism sector where diversification is currently low.

b. Strengthen education, particularly among fishermen.

2. INTRODUCTION

Around the world, people seek to understand the socioeconomic implications of climate change, including likely effects on the economy, strategies to minimize negative consequences, and ways to adapt to inevitable impacts. The Galápagos Islands provide an excellent case study for understanding climate change effects on biodiversity and human well-being because of the importance of nature to fisheries and tourism, the relative isolation of the islands, and the well studied local impacts of the El Niño-Southern Oscillation (ENSO) climatic phenomenon. ENSO events could be a proxy to understand the possible effects of climate extremes that might result

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from climate change, and ENSO events could themselves increase and become more intense with climate change.

Other chapters in this publication discuss the effects of climate change on ecosystems. In this chapter, we analyze the potential socioeconomic effects of these ecosystem changes. Given the close linkage between nature and society, these effects could be significant. Understanding the sensitivity of the tourism and fisheries sectors to climate change and the adaptive capacity of each to address these changes is essential for the development of present and future management strategies. More broadly, this assessment will be critical in gaining political and public attention to the actions needed to address climate change.

The focus of this chapter is to examine how tourism and fisheries —two of the most nature-based activities in the Galápagos Islands— will be affected by climate change and to what extent we can expect these industries to be able to adapt to these impacts. The chapter concludes with recommendations for helping these sectors, as well as the larger Galápagos society, adapt to climate change.

3. METHODS

Analyzing the potential effects of climate change on economies is a relatively new field. In developing the methodology for this study, we focused on two critical issues: (1) the likely effects of climate-related ecosystem changes on tourism and fisheries, and (2) the ability of these sectors to adapt to these effects. This approach complements global analyses examining sensitivity based on (1) employment and economic dependence and (2) adaptive capacity based on health, education, governance, and size of the economy (Allison et al. 2009).

Likely effects of climate-related ecosystem changes on tourism and fisheries: For the first component of the study, we analyzed the level of economic and social importance of fisheries and nature-based tourism. In particular, we examined the role of species and habitats in each sector to determine how the predicted climate change effects on these species and habitats, as discussed in other chapters, might affect fisheries and tourism. To do so, we investigated which species and habitats are most important to (a) fisheries, based on fisheries data and the biology of key species, and (b) tourism, based on tourists' rea-

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sons for visiting the Galápagos. We then examined the levels of employment and economic dependence associated with these two sectors, as measured by employment statistics and the percentage of the Galápagos economy attributed to each sector. These data served as an indicator of the sectors' sensitivity to change. As part of this analysis, we also considered (a) differences between the contributions of national versus international tourists to the economy, and (b) the contribution of fisheries and tourism to other economic sectors.

Ability of tourism and fisheries sectors to adapt to climate-related effects: For the second component of the study, we examined variables indicative of people's ability to adapt to new economic situations. These variables include: level of education, language skills, social and institutional support networks, access to alternative livelihoods, investment in the current sector, and Internet communication skills.

We used multiple methods to examine these variables, which ensured triangulation of information, and obtained quantitative data for statistical analyses and qualitative data for an in-depth understanding of the issues.

Literature review: To minimize duplication of previous research and to maximize our understanding of the issues, we conducted a literature review that included materials from government agencies, private businesses, non-governmental organizations, and peer-reviewed journals (see References and Additional Literature).

Tourist surveys[1]**:** We interviewed 400 Galápagos-bound tourists in the Quito airport over a 5-day period using a structured interview guide. This sample was statistically representative of tourists visiting Galápagos during the month of August.[2] The purpose of the interviews was to determine what attracted tourists to the islands. To obtain a general sense of the type of tourism presently occurring in the Galápagos, we asked visitors what types of activities (e.g. observation of wildlife, adventure sports, and nightlife) were central to their visit, and also asked them to auto-identify the types of tourists they are (e.g. tourist with general interest in and knowledge of Galápagos wildlife, tourist with specialized knowledge of Galápagos species and habitats, and visitor interested in adventure sports). Tourists also ranked the importance of specific species to their decision to visit, which allowed us to identify the species most critical for tourism, and thus the implications for Galápagos tourism as climate change affect these species.

Key-informant interviews: We used a "snowball" sampling scheme to select 35 key informants, defined as people known and respected for their knowledge on the issue and often representative of the community. Snowball sampling uses references from key informants to identify individuals with particular characteristics to be interviewed. This method identifies a set of informants that form a social network. The purpose of these interviews was to determine the adaptive capacities of the tourism and fisheries sectors based on their social, economic, and cultural capital. We interviewed each key informant for approximately one hour using semi-structured questionnaires.

1. Survey questionnaire and other information available upon request to author.
2. The sample size is based on a total population of 11,389 tourists who entered Galápagos during August 2008. The results were obtained with a 95% confidence level.

In addition, guides, conservationists, and tourism experts attending the Climate Change Vulnerability Assessment Expert Workshop in April 2009 were interviewed about the types of tourists presently seen in the Galápagos and possible effects of climate change on tourist visitation.

Household survey: We conducted a household survey on the three main populated islands: Santa Cruz, San Cristobal, and Isabela. The purpose of the survey was to determine key socioeconomic and demographic characteristics—at a very low level of social organization (i.e., household)—that determine adaptive capacity and vulnerability. The survey included 365 households, which is statistically representative of the population,[3] and collected information on 1,397 people. We selected street blocks randomly and then determined, based on block size, the number of houses to be sampled. Less than 1% of the respondents rejected the survey. This percentage was lower than expected, considering the high occurrence of surveys in the islands as well as the 2006 Galápagos Census,[4] which might have caused respondent fatigue.

4. CLIMATE CHANGE EFFECTS ON TOURISM

Other chapters in this publication examine the possible effects of climate change on different ecosystems and their functional biodiversity. We now consider how these changes may subsequently affect tourism. First, we examine the likely impacts on tourist visitation given the importance of nature to tourism. Then we consider the effects of climate change on the Galápagos economy and the people engaged in the tourism industry.

4.1. Sensitivity: Importance of Nature to Tourism

The opportunity to see emblematic species is one of the central reasons that tourists visit the Galápagos Islands, making it critical to understand potential impacts of climate change on ecosystem health. In tourist surveys, 81.3% of respondents ranked wildlife as "very important/may not have come otherwise" to their decision to visit the Galápagos, and an additional 6.75% ranked wildlife as "important, although not critical" to their decision (table 1). Furthermore, 17 of the 18 species included in the questionnaire were ranked as "very important/may not have come otherwise" by at least 33% of respondents (table 2).

3. The sample was established based on a confidence interval of 95%, which measures the probability of coverage for the parameters to be estimated with an error established. The error was a maximum of 5%, which measures the level of uncertainty in relation to the parameter. A rate of "no response" of 10% was also defined. If we assume that the proportion of households to be surveyed is π and the sample achieves an estimation p, then: $P(|\pi - p| < 0.05) = 0.95$
We used the following formula for the calculation of the sample size for a proportion:

$$n = \frac{N \; Z^2_{\frac{\alpha}{2}} \; \pi (1 - \pi)}{d^2 (N - 1) + Z^2_{\frac{\alpha}{2}} \pi (1 - \pi)}$$

Where: $\pi = 0.5$, the value with generated maximum variability; N is the population size, the number of households in the province; d is the sampling error (0.05); and Z value is 95% (z=1.96). The final sample includes 190 household surveys in Santa Cruz, 110 in San Cristobal and 69 in Isabela, for a total of 360. This is a representative sample of Galápagos households, with an over-sampling of Isabela and San Cristobal Islands, and with adjustments to Santa Cruz.

4. 2006 Galápagos Census is a *de jure* census that collected data only on permanent residents of Galápagos, regardless of their place of residence at the time the census was taken. Data was therefore not collected on visitors, temporary workers, and undocumented workers.

Table 1. Importance of activities to Galápagos tourists.

	Not important at all/ no influence	Important but not critical	Very important/may not have come otherwise	No answer
Viewing wildlife	2.34	6.75	81.3	9.61
Photography	3.90	23.12	60.52	12.47
Snorkeling	11.43	36.36	35.84	16.36
Beaches	18.96	38.96	28.31	13.77
Diving	42.60	21.56	16.88	18.96
Kayaking	53.51	20.52	4.42	21.56
Surfing	66.23	9.87	2.34	21.56
Nightlife	62.08	15.32	2.34	20.26
Fishing	67.53	8.31	2.08	22.08
Other	0.52	1.04	4.42	94.03

Table 2. Importance of species to Galápagos tourists.

	Not important at all/ no influence	Important but not critical	Very important/may not have come otherwise	No answer
Tortoise	4.2	16.4	65.7	13.8
Sea turtles	2.3	19.0	64.9	13.8
Marine iguana	4.4	24.4	57.1	14.0
Blue-footed booby	5.5	23.4	57.1	14.0
Penguin	4.2	26.5	55.6	13.8
Sea lion	5.7	29.9	52.7	11.7
Land iguanas	6.5	27.8	52.5	13.2
Red-footed booby	6.5	30.9	47.8	14.8
Lava lizard	10.1	30.9	43.4	15.6
Masked booby	8.1	34.8	39.5	17.7
Albatross	9.6	34.8	39.0	16.6
Galápagos hawk	10.4	34.8	38.4	16.4
Flamingo	12.7	36.4	36.4	14.5
Frigate bird	13.5	35.1	35.8	15.6
Sharks	13.2	35.6	33.8	17.4
Reef fish	10.4	38.7	33.8	17.1
Flightless cormorant	13.2	36.9	32.5	17.4
Finches	12.2	42.1	28.3	17.4
Other	0.3	0.5	1.6	97.7

Table 3. Importance of species to tourism; effects of El Niño events on these species; anticipated effects of climate change and overall expected change in species population from climate change.

Species	Importance to tourism indicated by % tourists who noted species as "very important /may not have come otherwise"	Previous El Niño effects (indicative of climate change effects)	Anticipated effect of climate change (see other biodiversity chapters)	Expected changes
Tortoise	65.7	During the 1997–98 El Niño, tortoises drowned in floods, and some died from falling down ravines. Reproduction declined due to increased vegetation and wet soils, which lowered soil temperatures and made nests unviable, and also due to introduced mammals (e.g. rats) and insects (e.g. fire ants) that attacked and killed hatchlings (Snell and Rea 1999).	High air temperature induces migrations to lower elevations. Temperature and rainfall variation affects the soil rendering nests unviable. Increase in invasive species (e.g. fire ants) reduces hatchling survival through predation.	Uncertain
Sea turtles	64.9	The 1982–83 El Niño led to a considerable drop in green turtle nesting at various beaches from 400–800 individuals per beach to fewer than 50 individuals per beach (CDF 2009).	Warmer temperatures (above 30°C) will affect nesting eggs, favoring the birth of more females and consequently adversely affecting populations. In addition, declines in macroalgae will limit diets, and beach erosion from sea-level rise will adversely affect nesting sites.	Decline
Marine iguana	57.1	The 1982–83 El Niño resulted in population crashes of up to 90% in some populations (Steinfartz et al. 2007 in CDF 2009). Hatchling mortality was reportedly as high as 90%, with an overall 45–70% mortality; populations subsequently recovered with an increase in fertility. Llerena et al. 2004 reported negative impacts after the 1997–98 El Niño, with recovery over four years (CDF 2009).	Marine iguana numbers are expected to suffer significantly, principally due to decreases in macroalgae, marine iguana's major food source, and decreases in the strength of ocean upwelling.	Decline

Source: Juan Carlos Murillo, pers. comm.

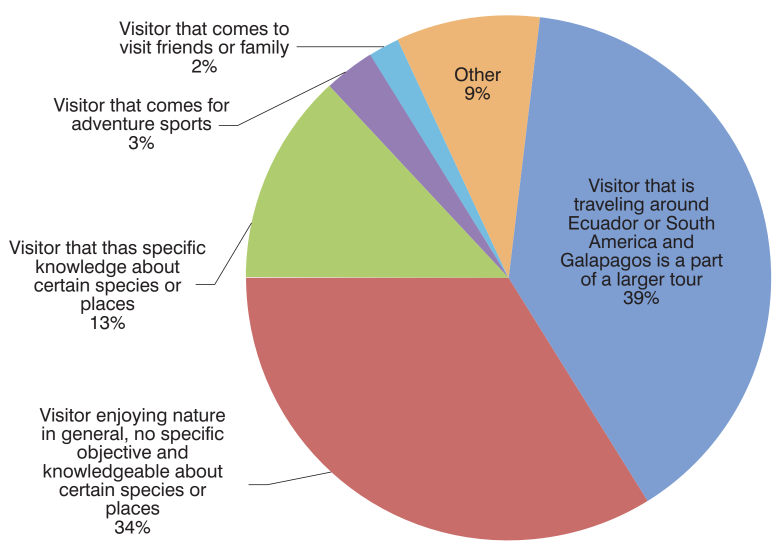
Species	Importance to tourism indicated by % tourists who noted species as "very important /may not have come otherwise"	Previous El Niño effects (indicative of climate change effects)	Anticipated effect of climate change (see other biodiversity chapters)	Expected changes
Penguin	55.6	This species experienced population crashes of 77% and 65% after the 1982–83 and 1997–98 El Niño events (Vargas et al. 2006 in CDF 2009). By the 1987 El Niño, the population was only approximately half as large as it had been in the early 1970s (Boersma 1998 in CDF 2009). Increased temperatures and rainfall favor pathogens such as *Plasmodium*, which have been detected already in penguins. It has been estimated that the Galápagos penguin has a 30% probability of extinction within the next century (Vargas et al. 2006 in CDF 2009).	The weakening of the Ecuadorian Undercurrent will adversely affect penguins and other cold-water-adapted species. This weakening will cause a reduction of nutrients and food for many marine species.	Decline; extinction likely
Blue-footed ooby	57.1	During the 1982–83 and 1986–87 El Niños, breeding colonies were abandoned and attempts at reproduction were unsuccessful (Valle et al. 1987; Anderson 1989 in CDF 2009).	High average air temperatures induce blue-footed boobies' migrations, increase adult mortality, and reduce reproductive success.	Uncertain
Sea lion	52.7	While different colonies responded differently to El Niño events, all colonies experienced significant drops in population numbers. During the 1982–83 El Niño, high pup mortality was observed (Trillmich and Limberger 1985). Pup production in 1983 was less than 30% of normal on the majority of islands, although wide variation between colonies was also noted (Trillmich and Limberger 1985). During the 1997–98 El Niño, a 50% decline in the sea lion population was observed, owing to 35% mortality and 15% relocation to other sites (Salazar and Bustamante 2003 in CDF 2009).	The weakening of the Ecuadorian Undercurrent will adversely affect cold-water-adapted species. The lowering of the thermocline could mean that sea lions will not be able to access their sources of food.	Decline
Land iguanas	52.5	Land iguanas are adapted to seasonal rain variation and rely on annual rainfall for nesting and survival of young (Snell and Tracy 1985). Therefore, they may be adversely affected by reductions in rainfall. Also, increases in the spatial distribution of tropical fire ants during El Niño events have posed a threat to land iguanas' nesting sites.	Increase in rainfall has a negative effect on reproduction (i.e., fewer, smaller eggs) and growth of egg-laying females.	Uncertain

4.2. Sensitivity: Anticipated Effects on Tourism of Changes in Emblematic Species

The seven most critical species for tourism (i.e., more than 50% of tourists indicated the species are "very important/may not have come otherwise") were tortoises, sea turtles, marine iguana, penguin, blue-footed booby, sea lion, and land iguanas. All seven are expected to decline due to climate change (table 3). Despite these declines, we expect tourism to endure in the Galápagos because of tourists' broader interest in nature.

More than half of the tourists surveyed indicated that emblematic species were critical to their decision to visit and that they may not have traveled to the Galápagos otherwise. However, the experience of naturalist guides, conservationists, and other experts who were present at the climate change workshop organized by Conservation International and WWF, some of whom were interviewed by our research team, indicates that most tourists will not stop coming if *some* of the emblematic species disappear. They noted that, unlike in the past, and although nature remains a priority reason for visiting, most tourists are not knowledgeable about specific species and habitats. This opinion is supported by the shift toward generic nature tourists and tourism that includes the Galápagos as part of a broader package. Our tourist surveys reported three times as many generic nature tourists (34% of tourists identified themselves as visitors enjoying nature in general) compared to expert nature tourists (13% of tourists described themselves as having more specialized knowledge of certain species and places) (figure 1). The remaining 53% comprised people traveling to the Galápagos as part of a longer trip in the region (38%), visitors interested in adventure sports (3%), people visiting friends or family (2%), visitors without a personal interest in the Galápagos but

Figure 1. Types of Galápagos tourists.



traveling with friends or family (1%), and others who either did not answer or did not fit into any of the given categories (9%).

Given the shift toward generic nature tourism, we believe that declines in some emblematic species will not result in significant drops in tourist visitation. Rather, the Galápagos will experience relatively stable tourism numbers or even an increase in visitation, as long as generic nature tourists and visitors seeking adventure and water sports continue traveling to the Galápagos. During El Niño years, when species such as penguins and marine iguanas suffered population crashes, guides noted that tourism continued largely unaffected. Only in the event of a threshold effect in which severe climate change leads to the *extinction* of *many* emblematic species will there be significant decreases in tourist visitation, owing mainly to a loss of generic nature tourism (i.e. not knowledgeable about species or ecosystems).

While our surveys indicate that nature-based tourism remains a large, critical component of the Galápagos tourism economy, non-nature tourism (tourism based on beaches and relaxation) and adventure and sports tourism (tourism based on activities such as kayaking or sport fishing) also draw people to the islands. These types of tourism may not be as sensitive to climate change as nature-based tourism, and they provide some income for the local population. However, they constitute only a small percentage of Galápagos tourism at present (see table 1 and figure 1), and if they were to grow, the long-term implications for economic viability would be adverse. As Watkins and Cruz (2007) indicate, adventure and sport tourism will attract clients only in the short term. Eventually, the Galápagos will need to compete with other destinations that can offer the same activities at more economical costs. While some prices could be reduced, the isolated location of the Galápagos would make it difficult to offer truly competitive rates. Furthermore, although some national tourists visit the archipelago for relaxation and the enjoyment of its beaches rather than the viewing of local wildlife, their numbers are minimal in comparison to generic nature tourists, and some of them may begin to consider less expensive beach options on the mainland or in neighboring countries.

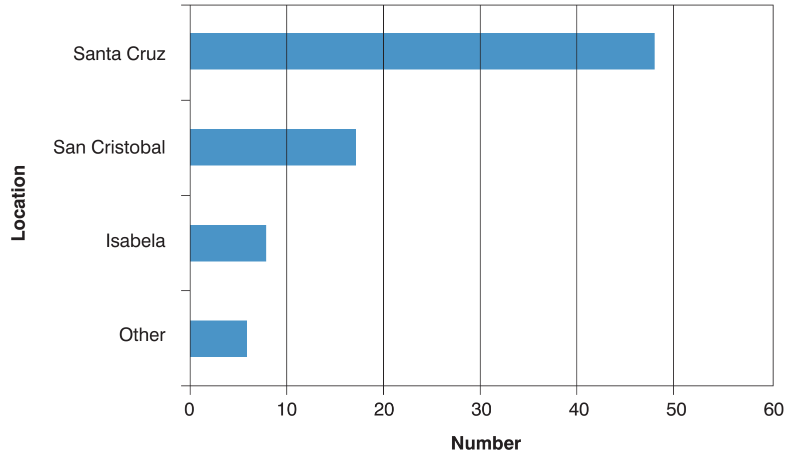
4.3. Sensitivity: Importance of Tourism Sector to Economy and Employment

As previously discussed, sensitivity of the tourism sector and the larger Galápagos society to climate change will depend on the severity of impacts on emblematic species. While climate change events that result in the decline or extinction of *some* emblematic species may only affect the tourism sector and the larger Galápagos economy marginally, climate events resulting in the extinction of *many* emblematic species would have sweeping negative effects. Generic nature tourism would collapse, leading to great losses of revenue and sources of employment. Currently, tourism revenues make up 77% of the Galápagos economy (Epler 2007) and total an estimated US$65 million annually (Epler 2007; Taylor et al. 2006). The tourism sector employs approximately 40% of Galápagos residents (Kerr et al. 2004). Survey results revealed that 55.7% of people involved in the tourism sector feel that the activity has improved their income, which suggests potential reductions in living standards if tourism were to decline.

Residents of Santa Cruz would be most affected by changes in visitation and spending. The tourism sector is concentrated on this island, with 50% of Santa Cruz residents employed in tourism (figure 2). Most of the live-aboard boat tours, from which the greatest revenues are generated, are based on this island, and 40% of these operations are run by local businesspeople (Taylor et al. 2006 in Watkins and Cruz 2007). In contrast to Santa Cruz, San Cristobal is home to the provincial government seat, and its economy has depended mainly on the public sector since the 1970s (Wilen et al. 2000). On Isabela, fishing is still an important economic activity, although in recent years both San Cristobal and Isabela have opened up more to tourism with the development of new hotels and activities. On Isabela, according to the 2006 Census, 8.6% of the population worked in hotels and restaurants (7.91% in fishing).

According to our tourist surveys, currently foreign tourists are mostly generic nature tourists, whereas Ecuadorian tourists are both generic nature and non-nature visitors. The disappearance of many emblematic species will mean a loss of the majority of international tourists, which in turn will result in substantial economic losses for Galápagos tourism and the local economy. National tourists spend a far higher percentage of their budget locally with a variety of vendors, leading to a multiplier effect (Taylor and Yúnez-Naude 1999). On the other hand, international tourists—who spend an average of US$4,180 in the islands (Taylor et al. 2006)—have a greater impact on the economy, as they tend to spend more money than the average national tourist (Taylor et al. 2006). Tourist interviews revealed that 37% of foreign tourists spend between US$2,000 and US$4,000, and 35% spend more than US$4,000. In contrast, 78% of national tourists spend less than US$2,000, and some spend as little as US$500 in total for airfare, transportation, food, accommodations and activities.

Figure 2. Location of tourism companies in the Galápagos.



Source: Hardner and Gómez 2004.

The tourism sector would experience a loss of revenue not only in the Galápagos but also on the mainland. Hotels and tours on the continent, domestic airfare between the islands and the mainland, and local travel agencies gross approximately US$100 million annually (Epler 2007).

What is more, the effects of climate change on the tourism economy could extend beyond the tour operators. Tourism provides money for conservation efforts, generating revenues for the Galápagos National Park, other local government institutions, and local environmental organizations. Since the enactment in 1988 of the Law of the Special Regime for the Conservation and Sustainable Development of the Province of Galápagos (LOREG), more money from tourism has remained in the archipelago as a whole, but most notably in political, administrative, and conservation institutions (Grenier 2008). In 2006, an estimated US$36.5 million was spent on the maintenance of government institutions at various levels (Diaz Guevara 2006 in Watkins and Cruz 2007). Approximately 40% of this budget derives from the tourism sector and the remaining 60% from the central government (Diaz Guevara 2006 in Watkins and Cruz 2007).

Another important complication of tourism sensitivity relates to the shift in the tourism industry from nature to non-nature tourism. This shift is already occurring and may accelerate as nature opportunities decline. This change might make the Galápagos less competitive and could lead to an undesirable cycle of cost-cutting and excessive growth (Watkins and Cruz 2007). Climate change also can cause changes in visitation patterns. It is predicted that as temperatures in tropical areas such as the Galápagos increase, tourists will begin to choose destinations with higher altitudes and latitudes where the climate is more attractive (Simpson et al. 2008). Severe weather, diseases, and carbon quotas also may make tropical destinations less desirable.

4.4. Adaptive Capacity of the Tourism Sector

In studying the adaptive capacity of people in the tourism sector, including boat tour operators, hotel and restaurant owners, land transportation providers, and guides, we found that this sector possesses various types of capital that will help them adapt to changes in tourist visitation and spending. In terms of cultural capital, people in the tourism sector have relatively high education levels in comparison to the rest of Ecuador. Nearly 40% of tourism respondents in the household survey completed high school, and a quarter have university or graduate degrees, compared to 22% and 18% respectively at the national level in 2001. People with higher education levels generally have more transferable skills and can earn more in the workplace. In addition, they have access to better opportunities both within and outside their home countries. Surveys also revealed that nearly 32% of respondents speak at least one language in addition to Spanish. Knowing multiple languages can give a person a competitive advantage, as it allows access to different opportunities locally and abroad. All respondents indicated that they are knowledgeable about and regularly use the Internet.

With regard to economic capital, our qualitative study revealed that people in the tourism sector have relatively solid financial standing. In addition to owning a house in the islands, some also have a house on the mainland. Banking and access to credit through formal institutions also are highly important in terms of their adaptive capacity. In the qualitative study, all informants reported having a checking account and access to credit in the *Banco del Pacífico* (Pacific Bank). Some people in the tourism sector have even made alliances with individuals outside of the islands to access funds for implementing their tourism projects.

Many tourism workers have large social networks that include family and friends in the islands and on the continent. Some have international ties and friends in different countries. Our study also showed that many people in the tourism sector belong to a formal tourism association that certifies them to perform activities as tour guides, hotel owners, or tourism agents; all of these extended networks provide emotional and economic support. However, the tourism sector has few strong grassroots organizations that could provide assistance, information, and strategies to help people to deal with climate change. There are some exceptions, such as grassroots networks of tour guides.

Many people involved in tourism in the Galápagos have alternative livelihoods (figure 3), indicating a general adaptive capacity. However, the picture is different when one looks at specific islands. Thus, one serious disadvantage for the adaptive capacity of tourism is that more than 56% of people in tourism on Santa Cruz—where tourism is concentrated—do not have alternative sources

Figure 3. Livelihood dependency of people employed in tourism industry.

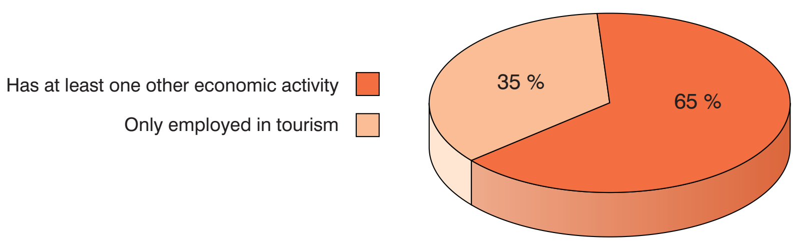


Table 4. Percentage of tourism workers engaged in alternative economic activities.

Alternative Economic Activities	San Cristobal	Isabela	Santa Cruz
Do not have other economic activity	11.1	N/A	56.0
Owner of business	11.1	N/A	4.0
Manual labor	N/A	11.1	N/A
Professional labor	N/A	N/A	8.0
Service or construction	N/A	11.1	N/A
Taxi driver or marine transportation	11.1	33.3	N/A
Commerce	N/A	N/A	16.0
Other	66.7	44.4	20.0

of income. The lack of alternative livelihoods makes them heavily dependent on the tourism industry and limits their adaptive capacity. Among those on Santa Cruz with another source of income were hotel owners who also owned a small boat, store, or business. In contrast, people in the tourism sector on San Cristobal and Isabela are better off in this respect, as 89% on San Cristobal and 100% on Isabela have a second source of income. Still, some of these San Cristobal and Isabela residents with alternative livelihoods will be affected to some extent because secondary jobs in transportation and local businesses have tourists as part of their clientele.

5. CLIMATE CHANGE EFFECTS ON FISHERIES

In this section, we consider the potential impacts on fisheries of biodiversity changes resulting from climate change. First, we analyze the importance of fisheries to the economy and employment in the Galápagos. Next, we examine the likely impacts of climate change on fish stocks, discussing species in order of importance to employment and the local economy. Finally, we consider the adaptive capacity of the fishermen and the industry.

5.1. Sensitivity: Importance of Fishing Industry to the Economy and Employment

Fisheries by nature are highly dependent on marine ecosystem health. Consequently, it is expected that climate change effects (positive or negative) on ecosystem health will directly affect this industry. Fishing intensity and the number of fishermen in the Galápagos increased from the late 1990s to the early 2000s, driven by demand from a growing population, a growing tourism industry, and international markets. Sea cucumbers are still highly prized by Asian markets as food and aphrodisiacs, and though illegal, shark finning is practiced to satisfy Asian markets. Lobsters are mainly exported to the United States, but they also are consumed within the islands and on the mainland. The establishment and growth of locally based tourism over the last three decades also has created a high demand for fish and other marine species such as slippery lobster, octopus, and conch.

Between 1999 and 2006, the number of registered fishermen increased from 795 to 1,006 (figure 1), and the fishing fleet doubled. It is estimated that currently there are between 436 and 466 active fishermen (Moreno 2007 in Castrejón 2008). Fisheries in the Galápagos account for an annual income of approximately five to six million dollars (Taylor et al. 2006). Isabela is most dependent on fishing for employment, but even there fishing constitutes only 7.91% of employment (INEC 2006).

Presently, the economic significance of this sector compared to others, including tourism, is small (table 5). Fishing constitutes less than 4% of the Galápagos economy (Watkins and Cruz 2007), and employs 4.92% of people in San Cristobal, 7.91% in Isabela and 2.29% in Santa Cruz. In all three islands, fishing is one of the least common sources of employment (INEC 2006).

Figure 4. Numbers of registered fishermen in Galápagos National Park and active fishermen in the sea cucumber and lobster fisheries.

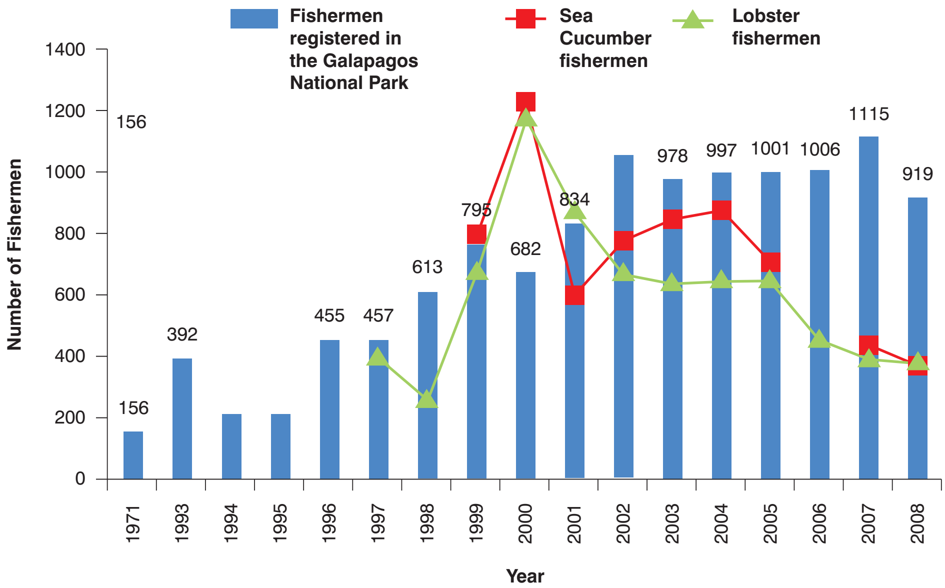


Table 5. Economic activities in San Cristobal, Isabela, and Santa Cruz Islands.

Economic activity	% of population employed in sector		
	San Cristobal	Isabela	Santa Cruz
Fishing	4.92	7.91	2.29
Agriculture	6.38	11.74	8.26
Hotels and restaurants	5.03	8.28	7.41
Construction	7.24	8.16	7.35
Commerce	10.09	10.63	11.67
Transportation and logistics	12.13	7.66	19.55
Public administration and defense	25.43	16.69	8.49
Teaching	7.99	5.56	4.98
Manufacturing	3.92	3.34	5.12
Others	16.87	20.03	24.88

Source: 2006 Galápagos Census.

5.2. Sensitivity: Species that Will Be Most Affected

In this study, we considered the extent to which commercially important fish species in the Galápagos may be affected by climate change. In order of economic importance based on total landing value, the main marine resources in the Galápagos are sea cucumber (*Isostichopus fuscus*), spiny red and green lobsters (*Panulirus penicillatus* and *P. gracilis*), and a variety of demersal white fish of the Serranidae family (*mero*, *bacalao*, *camotillo*). Large pelagic fish such as wahoo and tuna are important for local consumption, and small pelagic fish such as mullets, sardines, and mackerel are important for bait. Local people also consume other marine species, such as slippery lobster and octopus.

All of these commercially important species are either overfished or their status is unknown (table 6). Overfishing already has had an adverse effect on ecosystem health, and any negative effects of climate change, such as the warming of ocean waters, could worsen the decline of stocks. The extent to which any positive effects of climate change, such as expansion of tropical species' ranges, may compensate for the declines is unclear. One of the processes critical for the maintenance of many fisheries and one that may be threatened by climate change is the coupling of El Niño and La Niña. Many marine species reproduce and hatch their larvae during El Niño and need the cold, nutrient-rich currents of La Niña for larvae to survive. A decoupling of these two events caused by climate change may have adverse effects on various species of commercial importance.

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Table 6. Economic importance, market demands, current status, and expected climate change effects on commercially important fisheries in the Galápagos.

Species (in order of economic importance)	Importance to employment in fisheries (and/or to economy)	Market demands	Current status	Expected climate change effects	Overall effect
Sea cucumber	Declining number of fishermen, but still employs 25% of fishermen. Between July 2008 and January 2009, only 368 fishermen out of a possible 1,200 registered fishermen participated in the sea cucumber fisheries, which is the lowest number of fishermen since the 1999 season.	Highly prized by Asian markets.	Overfished, and catch is declining. In 2009, the fishery was closed due to low population densities.	Warmer waters and stronger flow from the Indo-Pacific may favor recruitment of sea cucumber and lobster populations following strong El Niño events. However, overfishing may occur because access will be easier as other species die out.	Increases after El Niño events, but possible subsequent declines.
Spiny red and green lobsters	Declining number of fishermen, but still employs 25% of registered fishermen (384 individuals).	Mainly exported to the U.S. Also consumed in the Galápagos and mainland Ecuador.	Overfished, but better managed than sea cucumber. In 2009, lower prices for spiny lobster meant that these fisheries were not as important. The stocks seem to be in a process of recovery.	Warmer waters and stronger flow from the Indo-Pacific may favor recruitment of sea cucumber and lobster populations following strong El Niño events. However, overfishing may occur because access will be easier as other species die out.	Increases after El Niño events, but possible subsequent declines.
Slippery lobster	Unknown.	Incidental catch of spiny lobster.	Unknown.	Warmer waters and stronger flow from the Indo-Pacific may favor recruitment of sea cucumber and lobster populations following strong El Niño events. However, overfishing may occur because access will be easier as other species die out.	Increases after El Niño events, but possible subsequent declines.

Species (in order of economic importance)	Importance to employment in fisheries (and/or to economy)	Market demands	Current status	Expected climate change effects	Overall effect
Near-coastal demersal fish (e.g. white fish, Galápagos grouper [*bacalao]*, [*mero*], cod and seabass [*camotillo*], and some coastal pelagics)	In 2009, the fishery was very important for local fishermen's income. Fishing is particularly important between September and March because of demand for these fish in mainland Ecuador.	Unknown.	Possibly overexploited. Demersals have declined in shallow coastal regions, resulting in fishing at seamounts and in deeper waters.	Higher temperatures are expected to cause range reductions in cold-adapted species.	Declines.
Large pelagic fish (e.g. wahoo, yellowfin tuna, big-eyed tuna, swordfish, sharks, and rays)	Important for fishermen's income year round. Consumed by the local population and by tourists in restaurants and tour boats.	Unknown.	Increasing pressure as fishermen shift from demersal species to pelagics. Big-eyed tuna overexploited. Yellowfin and wahoo close to capacity.	These species have affinity for warmer temperatures, so their populations may shift. Protection from industrial fishing fleet also will ensure stability.	Increases.
Minor benthic resources (e.g. octopus, *churo*, and *canchalagua*)	Important for local consumption. Exact numbers unknown.	Increasing demand from tourists and locals.	Unknown.	Intertidal habitats are expected to be affected by warming waters and lack of productive environment.	Declines.
Sharks	Difficult to estimate, as fishing sharks is illegal. There are reports from interviews with fishermen, particularly in Isabela, that sharks are an important source of income for some families of fishermen involved in the capture and trade of shark fins.	Frequency unknown but related to the demand in East Asian markets.	Specific data unavailable because capture is illegal.	Unknown.	Unknown.

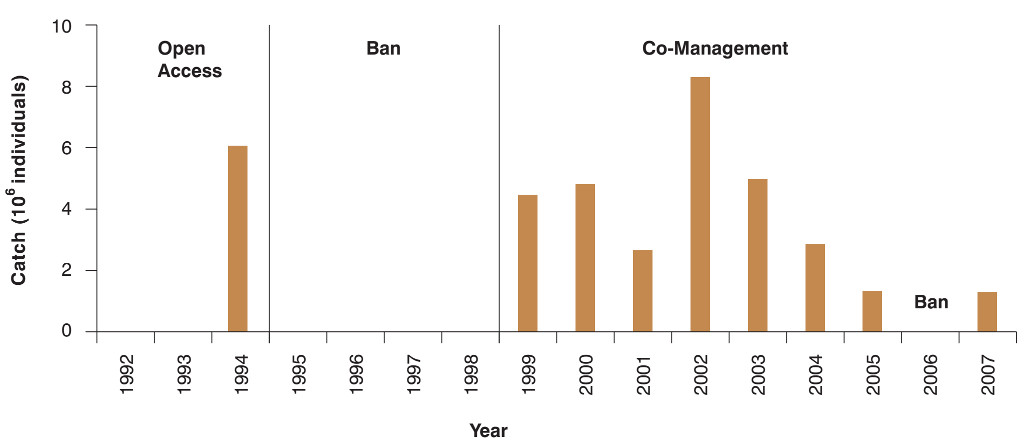
Sea Cucumber

This species already is heavily exploited (figure 5) due to overfishing, and it is expected to decline further with climate change, although brief post-El Niño increases may occur. While historically sea cucumber has been the most profitable fishery in the Galápagos, the number of people fishing for sea cucumber has declined substantially, mainly because of declining catch per unit effort (CPUE). Between July 2008 and January 2009, only 368 fishermen participated in the sea cucumber fishery, which was the lowest since the 1999 season (Murillo 2009). In 2008, fishermen in this fishery obtained revenues of approximately US$1,500 per month (Murillo 2009). Household surveys reveal that when the fishery was open, 21% of San Cristobal fishermen, 19% of Isabela fishermen, and 23% of Santa Cruz fishermen participated in the fishery, although not exclusively. The survey data indicate that fishermen would be affected equitably from all three islands if climate change were to drastically reduce this fishery.

Spiny Lobster

Like the sea cucumber, spiny lobster declined in the early 2000s due to overfishing (figure 6). However, spiny lobster populations have shown signs of recovery in the past two years due in part to effective management by the Galápagos National Park (Murillo 2009). Nonetheless, future climate change events could threaten this species, although brief post-El Niño increases may occur. While this is the second-most profitable fishery in the Galápagos, there are currently only 384 fishermen and 151 fishing boats in this fishery (Murillo 2009). The survey showed that 16% of San Cristobal fishermen, 19% of Isabela fishermen, and 23% of Santa Cruz fishermen participate in this fishery when it is open, and obtain revenues of approximately US$1,800 per month during the fishing season (Murillo 2009). All of the fishermen who participate in the spiny lobster fishery also participate in the sea cucumber fishery.

Figure 5. Annual catch of sea cucumber in the Galápagos Marine Reserve from 1992 to 2007.



Source: Castrejón 2008.

Slippery Lobster

The slippery lobster is an incidental catch of the spiny lobster fishery. Thus, the largest level of exploitation of the slippery lobster takes place during the spiny lobster fishing season from September through December. During the rest of the year, only a small number of fishermen fish for slippery lobster. The present state of the slippery lobster fishery is uncertain; no data exist on the density of the population. Nevertheless, fishermen may take a greater interest in the capture and marketing of the slippery lobster due to overexploitation of the spiny lobster fishery. Like the sea cucumber and spiny lobster, this species is expected to experience post-El Niño increases. However, as in all of these fisheries, climate change may transform some of the key ecological conditions, such as the coupling of El Niño and La Niña.

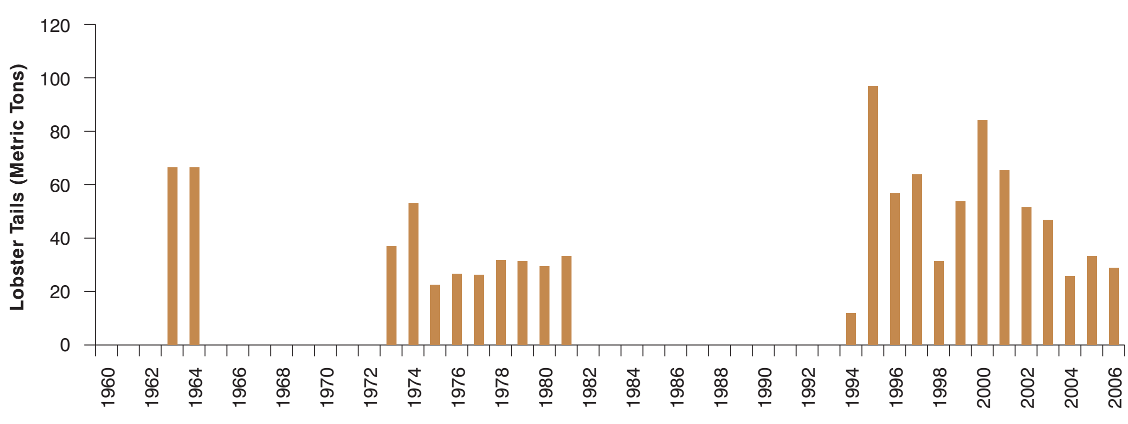
Coastal Demersal Fish (Primarily Grouper)

Coastal demersal fish populations have been overexploited, and fishing efforts are shifting to deep-sea demersal species (e.g. *mero*, *brujo*, and *camotillo*). These species are expected to decline further due to climate change-induced warming of waters. Fishermen in these fisheries have reported monthly revenues of approximately US$700 year-round, compared with US$1,500 per month for sea cucumber and lobster. There are approximately 200 fishermen in demersal fisheries, and a small portion of these fishermen also are involved in the sea cucumber and lobster fisheries (Murillo 2009). In 2009, 11% of San Cristobal fishermen, 23% of Isabela fishermen, and 14% of Santa Cruz fishermen were fishing for grouper, indicating that a modest portion of fishermen would be affected if demersals declined further.

Large Pelagic Fish (e.g. Wahoo, Yellowfin Tuna, Big-Eye Tuna, Mahi Mahi, and Swordfish)

These species also are under pressure, although their status is less clear. Wahoo landings increased from 7 tons in 1997 to 36 tons in 1998 and 39 tons in 1999. In contrast, tuna landings declined from 41 tons in 1997 to 10 tons in 1998 and 4.3 tons in 1999 (Fundación Natura 2002). One species of

Figure 6. Historical annual captures of spiny lobster (*P. penicillatus* and *P. gracilis*) in the Galápagos Marine Reserve from 1960–2006.



Source: Castrejón 2008.

tuna, *Thunnus obesus*, which is very economically important, is listed as vulnerable (Castrejón 2008). Shifts into this industry by demersal fishermen are expected to intensify pressure. Climate change actually may result in population increases due to the species' affinity to warmer waters, although any such increase may be eclipsed by fishing pressure. Qualitative interviews about previous El Niño events indicate that wahoo and mahi mahi captures increased. As pelagic fish are highly migratory, they could be more resilient to a reduction of upwelling. A shift to open-water fisheries, if properly managed, could possibly strengthen the resilience of the coastal ecosystem, provided that overall fishing pressure does not increase (CDF 2009). The same 200 fishermen in demersal fisheries also participate in pelagic fisheries (Murillo 2009). In 2009, 40% of San Cristobal fishermen and 29% of Isabela fishermen were fishing for tuna and wahoo, and 14% of Santa Cruz fishermen were fishing for wahoo. Tuna and wahoo are year-round fisheries, and interviews found that fishermen earn approximately US$700 per month for tuna and US$600 per month for wahoo. The pelagic fishery is becoming increasingly popular, including a shift to sport fishing. It may be a viable alternative to the heavily overfished sea cucumber, lobsters, and demersal fish, as long as the CPUE is capped at a sustainable level to avoid declines such as those already observed for tuna. Currently, an estimated 30% of the 200 fishermen in demersal and pelagic fisheries also are involved in the sea cucumber and spiny lobster fisheries (Murillo 2009).

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Minor Benthic Resources (e.g. Octopus, Churo, and Canchalagua)

Churo (marine snails), octopus, and *canchalagua* (chitons) are captured throughout the year and are increasingly being consumed by tourists and local residents. Presently, there is no regulation on the level of exploitation of these fisheries. The intertidal zone, in which these resources thrive, is expected to be one of the areas most adversely affected by climate change due to changes in temperature and salinity and a decrease in pH.

Sharks

According to interviews, illegal shark fishing is practiced by some fishermen from all of the islands, although it seems to be more common among fishermen in Isabela. This practice is important as a source of income for some fishing families. Data are not available on the frequency of illegal shark fishing or the effects of climate change on sharks, but this and other illegal activities lower the resilience of the ecosystem, which can exacerbate negative climate change effects.

5.3. Adaptive Capacity of the Fishing Industry

We found that Galápagos fishermen have characteristics that indicate a moderately strong ability to adapt to change. In terms of social capital, fishermen have strong social networks within the islands and on the continent. In addition, fishermen are members of cooperatives that provide institutional support when negotiating the fishing calendar and the total allowable catch of species with the GNP. Both of these networks can be critical support systems during times of hardship. With regard to economic capital, fishermen are able to obtain loans easily, which can provide them with alternative economic investment opportunities in times of change.

Perhaps the most important adaptive strategy of fishermen is that they are not specialized. Galápagos fishermen can engage in a wide variety of fisheries inside the GMR, providing them with more economic security. Furthermore, 90% of fishermen in Galápagos have alternative livelihood activities that supplement their income from fishing, though patterns vary by island. According to our interviews, when past El Niño events caused certain species to decline, some fishermen shifted to other activities, such as driving taxis or working in their own small businesses. Examples of other alternative economic activities for fishermen are agriculture, construction, tourism, and auto repair.

Despite these advantages, however, our surveys show that, in general, fishermen have low education levels and few speak other languages besides Spanish. Furthermore, only a small percentage of fishermen are knowledgeable about the Internet.

6. CONCLUSIONS AND RECOMMENDATIONS: ADAPTATION TO CLIMATE CHANGE IN THE GALÁPAGOS

6.1. Conclusions

Given tourism's heavy dependence on nature and the affinity of tourists for emblematic species, the tourism industry may be hard hit if climate change leads to the extinction of many of these species. A potential decline in generic nature tourism, which currently is the most prevalent type of tourism in the islands, is a significant concern because tourism is extremely important to the Galápagos economy and employment. Generic nature tourism driven by international tourists provides far greater revenues than non-nature tourism, and it provides financial support for conservation efforts. The residents of Santa Cruz, where tourism is concentrated, are heavily dependent on generic nature tourism for their livelihoods. However, Santa Cruz residents' education, language skills, institutional and social support networks, solid financial standing, access to credit, and Internet and communication skills will help them shift livelihoods.

Fisheries are highly dependent on healthy marine ecosystems. Consequently, it is expected that climate change effects—whether positive or negative—on ecosystem health will directly affect this industry. In particular, sea cucumber, spiny lobster, and coastal demersal fish, which are already in decline due to overfishing, will likely decline even further as warming waters reduce their habitat range and make them more accessible to fishing.

Although pelagic fish species may be affected positively by climate change, the potential benefits are likely to be outweighed by a shift in fishing pressure from coastal demersals to large pelagic fish. Because of the low contribution of fishing to the economy (less than 4%) and employment in Galápagos, however, any changes in the industry are not expected to have a significant impact on the Galápagos economy and employment. In addition, 90% of fishermen have alternative livelihoods, access to credit, and strong social and institutional networks, so they are in a moderately good position to adapt to climate change, despite their limited education and communication skills.

6.2. Recommendations

A. Enhance resiliency of species and habitats

We recommend enhancing the resiliency of the species and habitats at risk to climate change, particularly those that are critical to tourism and fisheries.

For Tourism

a. Protect the species that attract international tourists to the Galápagos: tortoises, sea turtles, marine iguana, penguin, blue-footed booby, sea lion, and land iguanas.
b. Develop strategies to address the uncertainty surrounding climate change. For example, key emblematic species may decline due to climate change, and marketing and promotion campaigns should be designed to accommodate these changes in a manner that continues to attract international tourists and maintains the image of Galápagos as a unique destination.

For Fisheries

a. Establish sustainable management measures for demersal fish, which are at particular risk from climate change, in new areas such as seamounts, but also in coastal waters. Study and improve conservation efforts for seamounts, mangroves, and other key areas so local people can use the areas in a sustainable manner. These areas have special importance for the region's biodiversity, but they have been little studied and local fishermen are increasingly exploiting the resources that can be found there. The vulnerability of these areas will increase with climate change.
b. Place an emphasis on protecting sea cucumber, spiny lobster, and demersal species from overfishing, as they are the most vulnerable to climate change.
c. Establish sustainable management regulations for pelagic species that may not be heavily fished currently but could become more important in the future due to climate change.

B. Enhance people's adaptive capacity.

Much can be done to enhance the adaptive capacities of people in the tourism and fisheries sectors, along with the larger Galápagos society. The challenge for authorities, conservationists, and communities is to implement win-win approaches that favor conservation but also reinforce the resilience of human communities.

a. Promote diversification of economic livelihood activities, particularly within the tourism sector where diversification is currently low. It is essential to develop sustainable economic activities that are not directly related to tourism and that can bring an alternative source of income to the local population to reduce dependency on the tourism sector. This is especially true in the case of Santa Cruz but also to some degree in San Cristobal. Fishermen and tourism workers could be included in conservation activities—monitoring of illegal fisheries, eradication of invasive species, and cleaning of the Park's marine and terrestrial areas—to increase the number of livelihood activities. With some training, local people also could participate in research activities as field assistants. Some people could become more involved in agriculture, especially organic agriculture, as is presently taking place with coffee.

b. Strengthen education, particularly among fishermen. As is true in many other parts of Ecuador, people living in the Galápagos have a low level of education, which limits adaptive capacity. This is particularly true for Galápagos fishermen, who have one of the lowest education levels of all of the sectors. Education must be enhanced because people who have more education are better equipped to deal with change in general and with climate change in particular, as they have more options to migrate or shift to other economic activities. A high-quality education that increases both general knowledge and specialized skills is essential to prepare the society for uncertainty and to lower general vulnerabilities. Students must be prepared to handle specific issues while simultaneously learning how to adapt flexibly to a changing world.

ACKNOWLEDGEMENTS

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Annex I

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Annex II

Declaration of Santa Cruz
Facing Climate Changes Together in the Galápagos Islands

Within the framework of the *International Workshop of Experts for the Analysis of the Vulnerability of Biodiversity and Human Wellbeing Associated to Climate Change in the Galápagos Islands* held from April 20th to 23rd, 2009 on Santa Cruz Island, with the participating organizations: Ecuadorian Ministry of Environment, the Municipality of Santa Cruz, the Ecuadorian Secretary for Planning and Development (SENPLADES), the Galápagos National Park (GNP), the Navy Oceanographic Institute (INOCAR), Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN), the Ecuadorian Agency for Agricultural Quality Assurance (Agrocalidad-SICGAL); representatives from Conservation International (CI), WWF, the Charles Darwin Foundation (CDF), the Universidad San Francisco de Quito (USFQ) and the participating experts.

Considering:

1. That the Ecuadorian government contemplates within the National Development Plan, especially in Objective 4, the identification of responses to climate change as part of its responsibility to its citizens and the entire World.
2. That the Ministry of Environment is developing the National Strategy against Climate Change.
3. That the Technical Secretariat of Risk Management is developing the National Policy of Risk Management.
4. That the Galápagos Islands, as part of the World Natural Heritage Sites, are a priority site, vulnerable to climate change due to its unique oceanographic, weather, biological and socioeconomic conditions.
5. That the Galápagos Islands are a strategic site and a natural laboratory generating biophysical information that will enable the Republic of Ecuador to prepare and help other countries in the Eastern Tropical Pacific region to plan and be able to face the challenges posed by climate change.

Agree:

1. To consider within the policies, strategies and plans for the Galápagos Islands, the recommendations and priority action plans identified by the experts in the workshop.
2. To create a Climate Change Working Group that will enable the formulation and implementation of an adaptation plan, according to the specific needs of the Galápagos; with the participation of public and local national institutions, educational and research centers, non-governmental organizations, private sector and local communities.
3. To apply the precautionary and intergenerational responsibility principles to manage existing pressures on the environment so as to increase resilience and adaptation against uncertainty of future conditions associated to climate change.

Santa Cruz, Galápagos Islands, April 22nd 2009, celebrating World Earth Day and celebrating the 50 years of the creation of the Galápagos National Park.

WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature by:

- Conserving the world's biological diversity.
- Ensuring that the use of renewable natural resources is sustainable.
- Promoting the reduction of pollution and wasteful consumption.

Building upon a strong foundation of science, partnership and field demonstration, CI empowers societies to responsibly and sustainably care for nature, our global biodiversity, for the well-being of humanity.

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